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ANALYSIS AND MODELING OF
INFORMATION HANDLING TASKS IN SUPERVISORY CONTROL
OF ADVANCED AIRCRAFT

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This report describes research and development centered on evaluation of information needs and automated management of information displays in advanced aircraft operations. Techniques for information selection were developed based on Multi-Attribute Utility (MAU) models and queueing theory formulations. These techniques take into account both subjective factors and objective situational conditions, as well as the immediate information monitoring and control needs of the operator and the impact on other (Con't)

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unattended processes. The combined MAU/queueing model was tested in a Monte-Carlo simulation. The experiment compared performance of the MAU-based policy to other priority policies both in event selection and information source selection. Initial results suggest that the value-based model is suitable for concurrent evaluation of information source and event sequence. The information management concept based on the MAU model seems to be superior to those based on traditional priority assignment. Possible applications of the approaches and the plan for further validation are also discussed.

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1. INTRODUCTION

1.1 Summary

This report covers the first year of a three-year program of research and development directed toward analysis of information needs and automated management of information displays in decision making and control of advanced aircraft. Its purpose is to establish new techniques for the selection of essential information in airborne tactical operations. The techniques center on the use of multi-attribute utility models, adaptive estimation methods, and queueing theory formulations to model individual supervisory control behavior.

Specific objectives of the three-year program include the following:

(1) Formulate a working taxonomy of supervisory control functions in advanced aircraft operations. Relate types of computer-based aiding to classes of supervisory control functions.

(2) Develop aiding programs for continuous information monitoring and control in advanced aircraft operations. The programs take into account the immediate needs of the operator and the impact on other unattended processes.

(3) Investigate experimentally the performance and domain of application of the continuous information monitoring and control programs.

(4) Investigate the behavioral issues of operator acceptance and confidence with the possible forms of model-based aiding.

(5) Develop explicit rules (in the form of a knowledge-based system) for controlling transitions between aiding forms.

(6) Produce guidelines for field application of the information evaluation and management programs in operational airborne systems.

In the preceding AFOSR sponsored program (AFOSR Contract No. F44620-76-0094), an information value model based on an application of adaptive multi-attribute utility (MAU) techniques was developed. A series of experiments using this model indicated that aided information selection, based on either the adaptive model or information seeking strategies elicited directly from the operator, resulted in improved task performance over manual selection (Steeb, et al., 1978, 1979). The program resulted in demonstrated techniques for information system evaluation and management.

The work reported here, the first year of a new three-year program, expands the domain of the information value model to include supervisory functions of monitoring continuous processes. The new model incorporates the adaptive MAU techniques into a queueing theoretic framework which is capable of describing continuous, multi-processing information seeking behavior. The work also deals with behavioral issues regarding operator acceptance and confidence in the model-based aiding, and explores possible techniques for on-line transitioning between forms of aiding through use of knowledge-based systems.

1.2   The Problem

The problems addressed by this research stem from the increasing supervisory loads imposed on the pilot in advanced aircraft operations. Future aircraft will be characterized by high information loads, severe time constraints,

and complex decisions regarding allocation of display resources. This is a prime example of the larger problem facing virtually all modern military command and control system--processing and selection among increasing large amounts of information. Local and remote computerized systems make available copious amounts of information concerning remaining resources, environmental state, potential computer aiding, and predicted circumstances and actions. In such cases, the costs of communications and the limited processing capabilities of the human operator make it necessary to optimize the information selected, processed and displayed.

The central problem in performing an analysis of information needs is the structuring of the decision process. On one hand, choices need to be modeled regarding continous variables such as the mix of information sensing, processing, encoding, transmitting and display at any point in time. Throughout this process, a balance must be maintained between maximizing operator awareness of system operation and minimizing communications costs operator task demands. On the other hand, event-driven activities such as situation assessment and execution strategies must be described. Finally, during the aiding process, transitions between different model forms must be made based on such situational criteria as system confidence, oeprator load and capability, and task characteristics.

Some initial efforts have been made toward analyzing and automating the information handling task functions. Information flow, load regulation, and control allocations techniques have been proposed using criteria based on queueing models (Chu and Rouse, 1979); dynamic programming algorithms (Tulga and Sheridan, 1980); optimal control models (Muralidharan and Baron, 1979); knowledge-based systems (Engelman, Berg, and Bischoff, 1979; Rieger and Stanfill, 1980) and multi-attribute decision models (Steeb and Freedy, 1976; Samet, 1978). This program represents an effort to develop, integrate and implement several of the more promising of these techniques.

1.3   Technical Approach

In brief, the information handling tasks in command and control situation
can be represented as a multi-level, multi-stage decision task of information
acquisition and action selection. At the top level is situation assessment
and plan generation where knowledge matching and heuristic techniques are
the general guides. At the intermediate level is monitoring and execution
where notions of urgency and utility apply.   At the lowest level is obser-
vation and control, where optimal control and observer models exhibit success.
In all le`......`, the effectiveness of the action decisions are dependent on the
appropriateness and timeliness of the information required. The choice
of what information to display thus reflect the task circumstances, the
operator's and automatic system's capabilities, and the communication channel
characteristics. These decisions can be expressed analytically using three
different methodologies: (1) through use of production rules guided by
pattern-directed process control, (2) through use of multi-dimensional sets
of utilities tied to the potential action consequences, and (3) through use
of sets of weighted criterion functions represented in terms of state-space
variables.

The program developed in the initial phases of this program concentrated on
the intermediate level of supervision functions, i.e., monitoring and exe-
cution, using a prescriptive utility analysis. With continuous supervision,
both descriptive process analysis and prescriptive utility modeling of opera-
tor information handling need to be elaborated. The initial MAU-based infor-
mation model handled the single-stage decisions present in airborne operations,
but did not deal with the many continuous behaviors present in monitoring
and sampling. Many of these continuous stochastic processes can be modeled
by embedding the MAU decision model in a queueing model. Here the time
distributions of potential events and the periods of attention demended for
information handling are assumed, and queues of potential messages or sampling

options are presented. The multi-attribute decision model is then incorporated as a criterion function in the queueing model. Estimates of system throughput, event delay time, and operator load along the time-line are provided as outputs of the queueing model.

1.4   Current Objectives

The focus of the work reported here is the expansion of the adaptive decision model to include continuous monitoring and control functions. The specific objectives that were addressed include:

(1)   Develop taxonomy of supervisory control functions organized along decision theoretic dimensions. Formulate relationships between task functions and forms of model-based aiding.

(2)   Determine key behavioral factors influencing operator acceptance and confidence with aiding. Ascertain effects of model confidence, aiding form and decision style on operator responses.

(3)   Expand the current MAU-based information model to include status appraisal and monitoring of continuous processes. This is accomplished by embedding the MAU formulation into a queueing model.

(4)   Test combined queueing/MAU model in Monte-Carlo simulation. Determine model response to different simulated operator styles and task demands.

1.5   Applications

The combined approach of adaptive information value estimation and the dynamic estimation of information traffic appears to be most applicable to decision tasks feature some or all of the following operational charateristics:

(1) <u>High Information Load</u>. The operator is in a time-stressed decision task. For each decision he can process only a portion of the available data set and must choose an action within a short time.

(2) <u>Costly Information Transmission</u>. The transmission of data to the operator is subject to cost, risk of detection, or limited transmission capabilities. Immediately valuable information must be selected.

(3) <u>Significant Judgmental Factors</u>. The decision maker must consider the credibility and content of the evidence along with the probabilities and utilities of the consequences associated with each ensuing action.

(4) <u>Multiple Competing Information Sources</u>. A variety of different systems or sensors must be monitored, and each unattended system increases in uncertainty over time.

Among the examples of actual military decision making situations which require such tasks are:

(1) Supervisory control and decision making in advanced aircraft.

(2) Air traffic control.

(3) Remotely piloted fleet guidance and control.

(4) Supervision of distributed subsystems and platforms.

(5) Satellite intelligence coordination.

(6) Supervision of air, ground, or sea support operations.

1.6   Report Organization

The organization of this report is as follows: Chapter 2 presents selected
approaches and concepts of control and supervision in advanced aircraft,
describes the development of an operational taxonomy of information handling
tasks, and reviews previous attempts in the development of analytical models
of operator information handling. Chapter 3 reviews selected model-based
aiding concepts, traces the development and verification of the adaptive
models, presents the continuous decision and control modeling concepts,
derives the MAU/queueing model, formulates the model description for a com-
bined multiple threat and flight management situation, and summarizes be-
havioral issues in computer-aided information handling. Chapter 4 describes
the procedures and the results of the Monte Carlo experiment for testing the
usefulness of the combined MAU/queueing model. Chapter 5 summarizes the
analytical and experimental results and presents a discussion of the research
findings and the future directions of the program.

2. INFORMATION HANDLING TASKS IN SUPERVISORY CONTROL

2.1 Overview

This chapter presents the results of an analysis of operator information handling tasks in advanced aircraft and a survey of previous modeling efforts in describing supervisory control tasks. The task analysis is descriptive in nature, with the intent of identifying task dimensions suitable for quantification and modeling under a supervisory control paradigm. The analysis also provides a basis for selection of the type of process modeling. Therefore, the emphasis has not been to develop a rigorous classification scheme, but rather to provide a framework for relating supervisory control tasks to forms of computer-based aiding. With this in mind, the study includes a brief literature review, technical discussions of related research areas, and analysis of task attributes related to information management. The topics discussed in the following sections follow the three hierarchical levels of goal achievement in information handling tasks: situation assessment, the collection and processing of data regarding the environmental state, monitoring, the comparison of current and desired states to determine necessary correcting actions, and observation, the estimation of states of a dynamic process.

2.2 Supervisory Control Tasks in Advanced Aircraft

2.2.1 Supervisory Control Paradigm. In general, the supervisory control paradigm applies to situations where an operator allocates his attention among various graphical or alphanumeric displays and intermittently communicates new programs to a computer which itself is in continuous direct control of a physical process (Sheridan, 1976). Supervisory control is becoming more commonplace, as the advance of computer automation and intelligent interfacing have changed the operator's role toward that of a supervisor

who plans, sequences, and coordinates. Succinctly, the broad sense of supervisory control can be defined as "Controlling a semi-autonomous system through the intermediary of a computer. The human supervisor performs upper-level goal-oriented functions such as planning system activities, programming the computer, monitoring the system behavior when computer-controlled, adjusting parameters on-line when appropriate, and intervening to take over control in an emergency or for normal reprogramming or repair." (Seifert, 1979.)

The initial idea of supervisory control narrowly referred to the task of monitoring automatically controlled processes and, when necessary, intervening and adjusting reference points. As an example, piloting an aircraft requires monitoring the aerodynamic configuration to ensure that the auto-pilot is working, trimming the set points to compensate for disturbance, and intervening in the case of autopilot failures and emergencies. When a process is automated or semi-automated, the control actions need not be continuously produced, and the operator need not devote full attention to that process. On the one hand, this makes vigilance and decision making behavior an important consideration, and on the other hand, this makes it possible for the operator to be responsible for multiple processes. As a result of these ramifications, the narrow sense of supervisory control can be expanded to include a broad spectrum of activities from control to supervision and planning.

An effective way to organize the broad spectrum of supervisory control functions is one according to the required activity levels. Singleton (1976) describes the levels of operator activities as follows:

> "At the lowest level he is an information processing
> device using eyes to scan instruments and hands to select
> data streams but he does this in the context of rules, pro-
> cedures, flight plans, aircraft performance characteristics
> and so on--his general situation knowledge. He is also
> monitoring his own performance in relation to long term and

> short term objectives, changing his and the computers
> strategy, adjusting his arousal level and even switching
> objectives. The computer will presumably aid him at
> different levels and participate in monitoring computer
> performance and human performance as well as hardware
> performance."

Johannsen and Rouse (1979) provide a schematic hierarchy of supervisory control in terms of loops for navigation, guidance and stabilization. While the inner stabilization loop represents continuous tracking, the operator activities in the outer loops becomes more and more discrete involving more mental activity such as decision making and planning. They also suggest the nature of human activity in the higher levels of the supervisory control hierarchy: "...the human is more of a 'satisfier' than an optimizer...What this means is that one should look at optimization with respect to broad criteria that allow multiple satisfactory solutions... humans simply do not worry about details until it becomes necessary to do so. Thus planning can be sketchy, perhaps in the form of scripts. Such sketchy planning can mean a drastic reduction in mental workload and also that the human has the resources left to deal with more tasks as well as the flexibility to react to unforeseen events."

2.2.2 <u>Supervisory Control Activities in Advanced Aircraft</u>. Analysis of supervisory control functions in advanced airborne systems is a particularly complex one as it involves complex, highly interactive types of activities determined by mission, system environment and subjective factors. Consider the pilot as the airborne system manager, facing a variety of information sources and displays--such as master monitor display, integrated multi-function display. These displays may be event driven, functional or procedural. The pilot has the responsibility to monitor the aircraft subsystems as well as supervise the autopilot and to detect possible hardware failures and potential hazards. The pilot must constantly respond to action-evoking events such as communication of tactical information, change of aircraft

configuration, and reduction of 4-D guidance errors. Also, the pilot is required to react to unexpected events such as identification of threat, change of flight plan, establishment of the backup mode, and declaration of emergencies, etc.

If the task is viewed as the totality of the situation imposed on the pilot, it appears that complete task descriptions should include activities and operator performance, as well as the task demands described in earlier sections. In studying the task analyses of a multiple intercept simulation experiment in our previous program, it was readily apparent that much of the subject's decision activities were devoted to the current, temporal information selection, although some efforts were also concerned with continuous probability updates. Additional considerations of advanced aircraft operations should include the operator's activities in defining, initiating and monitoring subtask execution. While the pilots usually accept the overall goal and plan as instructed, the process of organizing the activities of situation assessment and hierarchical planning at the top level, status monitoring and action execution at the intermediate level, and observation and control at the bottom level, is an individual one.

As described in Figure 2-1, the major subprocesses involved in situation assessment in the context of supervisory control of advanced aircraft include the following:

(1) Event sensing: directing sensors, establish communication and managing data flows.

(2) Data fusion: generating hypotheses and updating situations estimates.

(3) Problem recognition: identifying conflicts or porblems re-requiring resolution.

(4) Requirement analyses: defining actual activities required and possible intervening functions.
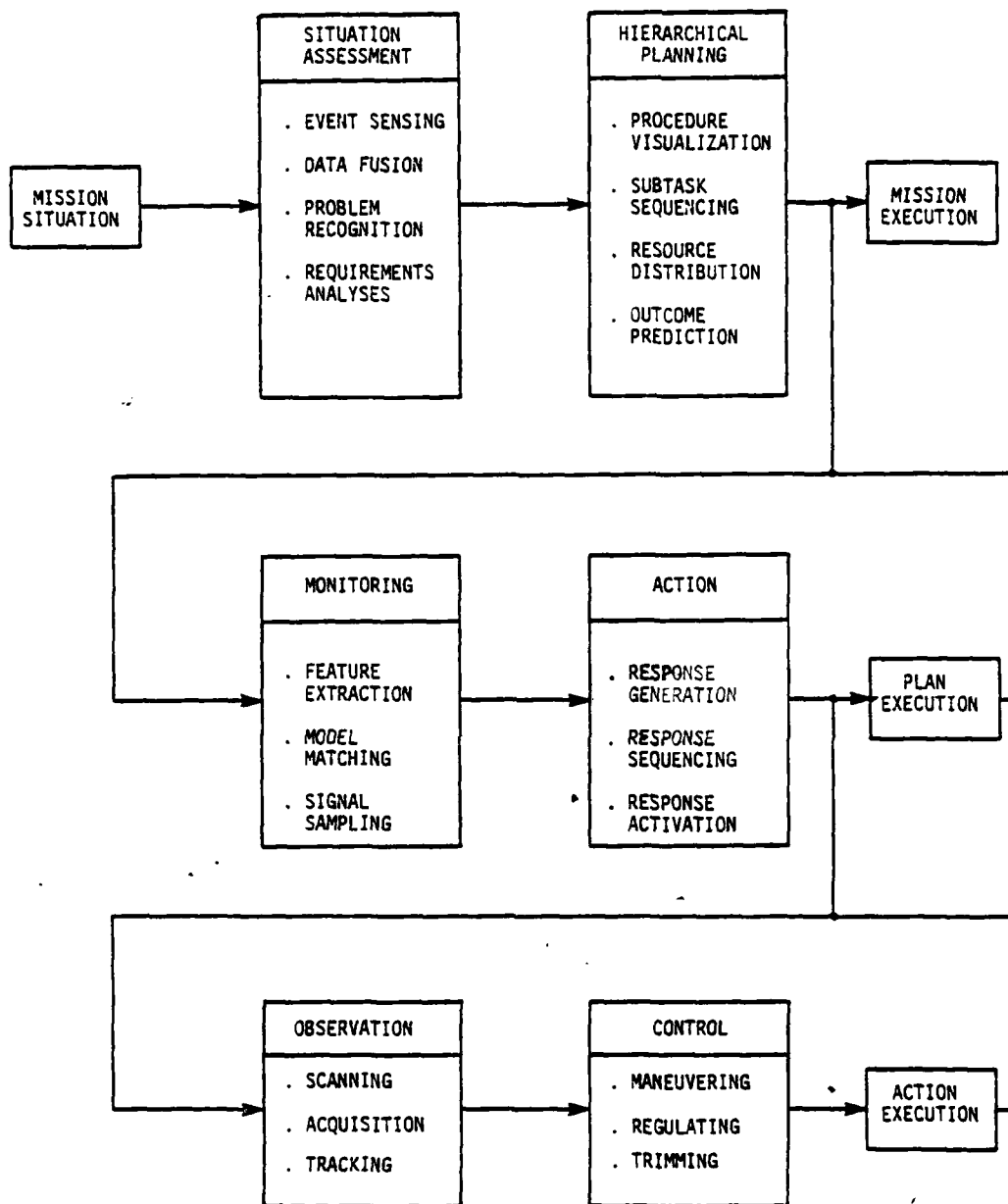
FIGURE 2-1.
SPECTRUM OF OPERATOR ACTIVITIES IN
SUPERVISORY CONTROL OF ADVANCED AIRCRAFT

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The situation assessment activities are tightly coupled with the hierarchical planning activities. These planning activities include procedure visualization, subtask sequencing, resource distribution, and outcome prediction. However, many of these mental activities are internal, not observable until some actions are taken in realizing the high-level assessment planning process. These observable actions are represented in Figure 2-1 as a lower level of activities (the monitoring/action pair). The major monitoring processes include:

(1) Feature extraction: partioning information into subsets assessing the relevance of a particular information set.

(2) Model matching: refining the hypothesis at the appropriate level of detail. Weighting the importance of situation states.

(3) Signal sampling: updating probability estimates. Reassessing the values and utility of potential outcome.

The action process, on the other hand, deals with response generation and execution issues. This monitoring action loop represents the major portion of in-task information handling, since many assessment planning activities are performed in pre-task fashion, and the trend toward future aircraft suggests that pilots will be less and less concerned with manual observation and control.

At the lowest level of the task hierarchy is the observation and control pair, which require continuous scanning, acquiring, and tracking a specific target or event of importance. Usually this lowest level involves the highest-frequency functions, such as target track and vehicle stabilization. These functions are typically automated, but unexpected events and system malfunctions may arise, making the operator back-up activities crucial. In the following discussion, we shall concentrate the intermediate level of supervisory control paradigm. The extensions of the analysis upward and downward will be achieved in the future programs.

2.3   Information Requirements and Information Handling

The selection and presentation of information in tactical airborne systems provides a prime example of a new type of interactive information management, in which the human operator must supervise and control a complex computerized system. The operator must, under considerable time constraints, weigh the probable usefulness and costs of a variety of competing forms of information--mission status, track data, environmental information, aerodynamic functioning, etc. These moment-to-moment judgments must often be based on subjective as well as objective factors, since the decision is normally too complex and dynamic to be analytically tractable. Therefore, the analysis of information needs and the optimization of information handling processes should be conducted prior to the design of airborne information system. This section represents our initial attempt to categorize the information types required in airborne decisions and the modeling approaches for operator information handling processes. The purpose of the analysis is to identify critical dimensions of information handling tasks and appropriate forms of computer-based information management.

2.3.1   Information Requirements in Supervisory Control. Although there exists an extensive literature base covering information requirements in airborne operations, few researchers have performed analyses at the operator interaction level. Most analyses considering user interaction follow mission-function-subfunction breakdowns of system requirements relating to the operator. For our purpose, the determination of the relationship between information handling for decision and automated management functions requires different forms of classification than have been present in most previous work.

The typical advanced aircraft mission can be defined most simply as a series of mission phases, much like the stages of the RPV supervision task analyzed in our earlier program (Steeb, Chen and Freedy, 1977). Typically, the flight operations consist of (1) takeoff, (2) climb, (3) rendezvous/cruise, (4) descend/loiter, (5) air-to-ground or air-to-air combat, (6) climb, (7) cruise, (8) descend, (9) approach, and (10) landing. Another level of decomposition, such as the one given by Zipoy and his colleague (1970) and shown in Table 2-1, is that of task analysis. At this level, the system and task requirements on the operator are described along with operator activities. A more detailed analysis of the task functions may be accomplished using a task breakdown according to the functional requirements or procedure decomposition into finer subfunctions, but the usefulness of the analysis in describing operator information needs may be limited. Instead, the information analysis that should be performed is one employing situation description along major spatial or physical dimensions on one hand, and subjective and decision dimensions on the other. For a complete description of a task at this level, it is necessary to include both *sequence* information which describes the order in which tasks are performed, and *taxon* information, which describes the conditions under which a given task is performed.

As an example to distinguish between taxon and sequence information, consider the air-to-air combat function shown in Table 2-1. The sequence information, or possible sequence one might follow, is (1) monitor and control airplane, (2) navigate, (3) communicate, (4) provide identification, (5) monitor threat situation, (6) search, acquire, and track target, (6) identify target, (7) deliver weapon, (8) escape weapon effect, and (9) evade enemy action. The taxon information used to ascertain the need for navigation include factors related to attack maneuver and terrain profile, such as closure rate and angle, threat potential, terrain altitude, release distance and track. If some certainty levels (or subjective confidence levels) are not reached, then navigation procedure is invoked, in which steering and maneuver-to-position information are computed and evaluated. The next-level sequence

TABLE 2-1

INFORMATION REQUIREMENTS AND OPERATOR TASKS
IN AIR-TO-AIR COMBAT (ZIPOY, ET AL., 1970)

FUNCTION NAME	SYSTEM INFORMATION	OPERATOR'S TASKS
MONITOR AND CONTROL AIRPLANE	FLIGHT PARAMETERS: PITCH, ROLL, YAW, ALTITUDE, ELEVATION, ETC.	CONTROL, MONITOR, AND BACKUP
NAVIGATE	ATTACK MANEUVER, TERRAIN PROFILE, TIME TO GO	SELECT EQUIPMENT/MODE; MONITOR AND OVERRIDE WHEN NECESSARY
COMMUNICATE	TRANSCEIVER STATUS; TRANSCEIVER VISUAL SIGNAL; VIEW FREQUENCY; TARGET DESIGNATION	SET TRANSCEIVER MODES; ENTER TARGET INFORMATION
PROVIDE IDENTITY	VISUAL/RF/IR; EQUIPMENT STATUS	VISUALLY IDENTIFY; SELECT EQUIPMENT/MODE/CODE; MONITOR AND TEST
MONITOR ENEMY ACTIVITY	RF/IR/VISUAL; MULTISPECTRAL SENSING; THREAT CHARACTERISTICS; FRIENDLY CHARACTERISTICS	ACTIVATE RF/IR, OBSERVE WARNINGS; CROSSCHECK AND REDIRECT OTHER SENSORS
OFFENSIVE COUNTERMEASURES	DETECT THAT COUNTERMEASURES ARE BEING EMPLOYED BY ENEMY	MONITOR ACTIVE OFFENSIVE COUNTERMEASURES
PREPARE FOR COMBAT	STORE STATUS; WEAPON/SENSOR MODES; GUIDANCE PARAMETERS; MANEUVER LIMITS	VERIFY STORES SENSORS; LIFE SUPPORT, CG, PROPULSION, SECONDARY POWER
SEARCH, ACQUIRE, AND TRACK TARGET	TARGET/SENSOR MATCH; TRACKING NEEDS BEARING, DISTANCE, CLOSING RATE, ANGLE CHANGE, AND ANGLE RATE	MONITOR AND CONFIRM TARGETS, AID VISUALLY IN SEARCH, ACQUISITION, AND TRACK; MONITOR AND FOLLOW STEERING COMMANDS AND SPEED CUES; VERIFY COMPUTATIONS WITH OTHER AIDS AVAILABLE.
IDENTIFY TARGET	MONITOR ENEMY ACTIVITY	MONITOR ENEMY ACTIVITY; INITIATE ACTIVE IDENTIFICATION AND MONITOR
DELIVER WEAPON	WEAPON SYSTEM PARAMETERS; FOLLOW ON	MONITOR OR PERFORM FOLLOW ON REQUIREMENTS
ESCAPE WEAPON EFFECT	MONITOR AND CONTROL; NAVIGATE	MONITOR, BACK UP
EVADE ENEMY ACTION	MONITOR AND CONTROL; NAVIGATE; RADAR/IR ACTIVITIES; COUNTER-MEASURE STATUS	MONITOR PRESENCE OF IR/RADAR; VISUALLY ALERT; RELEASE COUNTERMEASURES; COMMAND THAT WEAPONS BE JETTISONED

information may include (1) observe air speed, control, (2) observe ground speed, control, (3) monitor heading, control, (4) select navigation mode, (5) select way points and destinations, (6) observe, monitor and update position, (7) monitor bearing, distance and time to way point, (8) observe altitude, altitude rate, (9) select target and enroute target information, and (10) monitor system status. Requirements for information handling subprocesses will be discussed in the following section along these two dimensions.

2.3.2 <u>Taxon Information Requirements</u>. In general, the taxon information in real-time supervisory control involves one of the following activities:

(1) Continually sense and symbolically characterize all information with respect to the operation ranges and their relative importance.

(2) Continually update situational hypotheses, by hypothesis formation, model selection and experimentation (accessing information).

(3) Systematically relate maneuvers and action sequences to verifiable consequences.

(4) Provide "maximally" consistent interpretation, by keeping track of focus-of-attention (e.g., target) and resolving ambiguities or contradictions.

In our previous study (Steeb, et al., 1979), the taxon information were analyzed along decision dimensions, characterizing the situation by the danger or frequency of threats, the time available for decision making, and the options and characteristics of information concerning the aircraft and the environment.

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"The information available at a given time is dependent
on the environmental situation, the sensor characteris-
tics, the data base content, and the display capabilities.
The information itself may consist of data regarding
weather conditions, aerodynamic status, target track,
ECM, and mission status."

The costs of acquiring information result from the sensor characteristics,
the direct and indirect costs of sensor deployment, information processing
and display, and the amount of attention the operator can contribute. The
direct costs of information acquisition include such factors as energy
expenditures and equipment expenses. Indirect costs include increased
possibilities of detection and countermeasures. The available operator
attention, finally, is defined by the task demands and the individual capa-
bilities of the operators.

The costs and payoffs associated with the various possible outcomes vary
with mission phase. The consequences are defined not only in terms of
attrition of equipment and attainment of objectives, but also as a function
of organizational policy and procedures. The relative importance of fuel
expenditures, vehicle survival, countermeasures, etc., change as the mission
objective is approached, attained, or past. The relative importance of
these factors must be assigned by the human operator or by the command
group.

Available time for decision making varies throughout the mission as a
direct function of the varying vehicle speed, altitude, and surrounding
weather conditions. Altitude, cloud cover and ECM determine the distance
that obstacles, navigation points, or targets can be observed. The speed
then determines the available time. Decision time can be expected to
influence the amount of information that can be processed and the probability
distribution of the possible consequences.

The above analysis is based on a multiple-threat intercept scenario developed in a previous study. Quite coincidently, an analysis was performed based on a flight management scenario by Rouse and Neubauer (1978) and resulted in a similar set of information requirements: (1) type of information (reports vs. forecasts), (2) time period, (3) uncertainty, (4) cost (fixed vs. recurring), and (5) format. As the purpose of their study was to define the attributes of an information system from the design point-of-view, the following interpretation of the above information characteristics were given. Type of information includes reports of what has happened or is happening, and forecasts of what might happen. Time period refers to the time interval which the report or forecast covers. Uncertainty reflects the finite sample sizes upon which reports are based or the likelihood that forecasts are based on imperfect models. Cost can vary in type and magnitude. Fixed costs apply to information sources that incur no additional cost after they have been initially acquired. Recurring costs are those that are incurred every time an information source is used. Some information sources may involve both fixed and recurring costs. Reduction in uncertainty may incur extra cost. This information cost and uncertainty involve a tradeoff for a manager. The format of an information system involves the way in which the manager queries the system and the way in which the system responds. Examples cited include menu keyboard, voice, or free format such as graphics and other physiological links.

It appears from these two studies that common dimensions can be identified for the purpose of information management of multiple information sources at various stages of processing. The information sources vary from system to system and from mission to mission. One hypothetical set of information source used in our earlier study include threat displays at five levels of detail based on target type discrimination and lateral localization. In a broader set of flight management functions, Wempe (1974) includes the following sources that need to be attended in different stages of status apprisement and monitoring:

Navigation:	4-D Position Relative to Flight Plan
Guidance:	Current and Predicted Trajectory
Control:	Autopilot and Manual Operating Modes
System:	Configuration, Capabilities and Reserves
Environment:	Weather, Traffic, Terrain, Airport, and Ground Ratio
Clearance:	Flight Plan and Options

2.3.3 <u>Sequence Information Requirements</u>. The second aspect of information requirements, the sequence information, also can be summarized into three categories: (1) action sequence in serial operation, (2) action disjunction/ conjunction in parallel operation, and (3) action repetition. Related to such procedure information are the plan-related monitoring and execution activities, which will be described in detail in the next section and next chapter. Suffice it to say here that a planning process, in general, extends the above functions to include identification (recognizing elementary action/execution or previously conceived action procedures), and the reformulation and synthesis (experimenting, tradeoffs between taxon and sequence information). Depending on task situation and operator style, the set of supervisory control functions can be grossly classified into global supervisory and local interactive control. The former emphasizes situation assessment and monitoring while the latter emphasizes execution and action implementation.

At the global supervision level, the information requirements can be lumped into taxon information and procedure information or a task data base block and task execution block, respectively. The task data base may include one or more of four types of information (Fleishman, 1975):

(1) Behavioral description: description of actual activities required.

(2) Behavioral requirements: description of operator intervening functions.

(3) Ability requirements: description of operator abilities required in performance.

(4) Task characteristics: description of task conditions that elicit performance.

The task execution block will require procedure ifnormation that enables the processes to (1) *identify* primitive actions, or previously defined procedure, (2) *decompose* through conjunction/disjunction or repetition, and (3) *reformulate* subtask goals for easier identification or decomposition. Information from these processes, combined with that of control modes available and command structure constitutes the procedure information required for the task execution block.

At the interactive supervision level, the use of taxon and procedure information is not as clear-cut as at the global level. In general, taxon information is required in (1) cognition of the environment and status apprisement, and (2) monitoring processes; while procedure information is required for (3) executive function, and (4) plan update/recovery processes. Three types of procedure information may be used in interactive supervision: (1) pre-planned localized protocols, (2) asynchronous localized planning, and (3) iterative localized planning. In preplanned protocols, each monitor-action pair carries explicit taxon information that is globally accessible by other pairs. In iterative planning, global accessing and local processing alternate in a synchronized manner and communication bandwidth requirements between processes are low. In asynchronous planning, exchange needs to be made between processes as to goal, constraints, and sequence. Communication bandwidth requirements are high but internal processing requirements are low. These three types of information correspond to subtask planning requirements of identification, decomposition, and reformulation in one hand, and to subtask execution requirements of selection, acquisition, and processing in another. This concept of information handling subprocess will further be elaborated in Section 3.3. To sum up

information requirements of interactive supervision, the following dimensions appear to discriminate between task activities and performance:

(1) Situational scope. This is the 4-D extent of the region which must be dealt with; the space and time envelope within which all activities (information gathering actions, responses) lies.

(2) Situation dynamics. The rate of change of the situation state; the frequency of update of the situation estimate.

(3) Situational uncertainty. The prior uncertainty surrounding the state estimate(s).

(4) Situational complexity. The number of hypotheses necessary to represent the situation.

Studies are currently being performed by several researchers in describing and modeling the operator in processing procedural information, including work from a control and estimation point-of-view (e.g., Baron, et al., 1980), from a problem-solving point-of-view (e.g., Johannsen and Rouse, 1980), and from a formal language point-of-view (e.g., Pew, et al., 1978).

Baron and his colleagues have investigated the activities and procedures of flight crew in approach-to-landing. The intent is to provide a model for analyzing operator activities including information processing, flight control, decision making and communication. The assumption is that the operator has a number of procedures or tasks that may be performed at each instant. Six types of procedures are considered. (1) Vehicle control (maneuver, regulate, retrim), (2) Request (flap request, gear request, checklist initiate request), (3) Subsystem (altitude alert monitr/control, miscellaneous subsystem monitor/control), (4) Acknowledgement (checklist item), (5) Terminal approach (standard or monitored), and (6) Miscellaneous procedures (general message processing, landing parameter selection). Therefore, the operator has to decide the procedure to do next among the

alternatives. The selection is assumed to be based on the expected gains (i.e., urgency/priority and value) for executing a procedure. The information processing and control behavior on the other hand is modeled after the optimal control model.

Johannsen and Rouse (1980) consider the planning process of aircraft pilots in emergency and abnormal situations. It is proposed in the study that the human operator's planning process is hierarchical in nature, with the degree of detail in the hierarchy ranging from broad and sketchy to narrow and concise. The objectives of the study involve determining the sensitivity of planning variable to various subjective and objective variables and correlating planning activity with performance and workload. Their experimental studies show that the depth of planning is strongly related to probability of increased difficulty and weakly related to the criticality of the task situation.

A formal description of operator activities related to information handling can be found in Pew, Wood, Steven, and Weene (1978). A series of operations, iterative statements, and conditional statements that can serve to place activities to be performed are identified in a command and control, flight planning scenario. An example set extracted from Pew, et al. (1978) is given in Table 2-2. The approach allows natural translation to computer-oriented system requirements and easy allocation of computer and human responsibility for each activity.

Our view of information handling incorporates the above points-of-view and emphasizes a decision-oriented information architecture to describe operator's active, rational information processing activities. The operator is assumed to base his decisions on his internal model of the task environment. Information arrives in the internal model via sensor events, communication events, or maneuver events, etc. As such, the activities under study are largely driven by the priming of external events plus internal evaluation and require

TABLE 2-2

ELEMENTS OF THE PROCEDURE DESCRIPTION (PEW ET AL., 1978)

BASIC PROCESSES

    CLASSIFY OBJECT INTO ONE OF CATEGORY-LIST
    COMPOSE MESSAGE ABOUT INFORMATION
    COORDINATE WITH PERSON ABOUT INTERACTION
    COUNT OBJECTS IN RECORD
    DECIDE DECISION
    DELETE ENTRY FROM RECORD
    INFORM PERSON ABOUT INFORMATION
    LOCATE OBJECT ON DISPLAY
    LOOK-UP ATTRIBUTE OF OBJECT IN RECORD
    MEASURE-DISTANCE FROM LOCATION TO LOCATION
    NEGOTIATE WITH PERSON ABOUT PROBLEM
    OVERVIEW RECORD
    RECEIVE-MESSAGE FROM PERSON ABOUT INFORMATION
    RECORD ENTRY IN RECORD
    RESERVE-PLACE FOR ENTRY IN RECORD
    REQUEST INFORMATION FROM PERSON
    RETRIEVE RECORD FROM FILE
    SELECT OBJECT FROM ALTERNATIVES
    TRANSFORM VALUE IN FORM TO FORM
    ADD NUMBER PLUS NUMBER
    DIVIDE NUMBER BY NUMBER
    MULTIPLY NUMBER TIMES NUMBER
    SUBTRACT NUMBER FROM NUMBER

TESTS

    INFORMATION IS CONSISTENT WITH INFORMATION
    INFORMATION IS NOT CONSISTENT WITH INFORMATION
    NUMBER IS EQUAL TO NUMBER
    NUMBER IS NOT EQUAL TO NUMBER
    NUMBER IS GREATER THAN NUMBER
    NUMBER IS LESS THAN NUMBER
    NUMBER IS MUCH GREATER THAN NUMBER
    NUMBER IS MUCH LESS THAN NUMBER

CONTROL

    IF TEST THEN OPERATION(S) ELSE OPERATION(S)
    INTERRUPT PROCESS AND THEN OPERATION(S)
    FOR-EACH OBJECT IN RECORD DO OPERATION(S)
    UNTIL TEST DO OPERATION(S)

both taxon and sequence information. The analyses of operator's activities in the following section will concentrate on the relatively proceduralized tasks and value-based decision activities of the operator.

2.3.4 **Categories of Computer Aiding**. The various information handling subprocesses described in the previous sections indicate the possibility of aiding the operator at a number of levels. The levels range from simple aggregation to complete information system management, and different ones may be invoked according to the situational demands and operator needs. The levels correspond roughly to the five levels of automation recommended for future airborne information management systems (Mertes and Jenney, 1974). The various levels are described below in order of increasing complexity.

Aggregation. The decision aiding system has access to event likelihoods, situational data, and preference data. Aggregated information may be abstracted and presented to the operator for use in decision making. For example, the system may ascertain the immediate likelihood of enemy threats, the expected effectiveness of an avoidance maneuver, or the fuel consumption anticipated for a climbing attack. A number of probability aggregation displays have been demonstrated in making diagnostic decision about reconnaissance data (Howell, 1967). Howell states that improvements in diagnostic decision of about 10-15% can be expected with automated aggregation. Improvements become particularly noticeable under conditions of time or load stress or low input fidelity (Kelly and Peterson, 1971).

Alerting. The aiding system may sense an out-of threshold condition requiring operator intervention. An alerting display can be shown to the operator along with a description of the problem. This is especially important for monitoring of infrequent or long duration events (Mertes and Jenney, 1974). Again, no action recommendation is made, although explanations may be provided.

Option Recommendation. The aiding system may recommend information to acquire or actions to execute. The multi-attribute model represents the policy of the specific user. It has access to the factors characterizing each information choice, and it has inputs from the queueing model. The model can thus be configured to scan the available information sources and action options, and recommend the immediately most effective choice.

Because of the "look-ahead" approach implicit in the aiding system's decision tree, the reasons for alternative selection can be automatically generated and presented to the operator. For example, in a multiple intercept situation, the pilot may want to know why the computer recommended a change to low azimuth track-while-scan radar mode. Rather than simply giving numerical comparisons, which are hard to decipher, the decision tree may be analyzed and translated into meaningful information about likelihoods of target acquisitions and the effects of associated engagement maneuvers.

Information Management. The functions of recommendation may be extended to automation by linking the aiding system to the onboard information control system. The model may be used to direct the sensing systems, to select information, and format the data display to the operator. This process may be accomplished through use of weighting matrices specifying the effects of the various information sensing and formatting choices on the actions (see Steeb, et al., 1979 for a description of this procedure).

2.4   Approaches to Modeling the Operator Information Handling Task

2.4.1   General. As described in previous sections, the selection and presentation of information in tactical airborne systems provides a prime example of a new infomration management demands. Also, the operator's activities in information handling, selecting, acquiring and processing, can only be described as multiple processes, resulting from interaction

with multiple targets, multiple sensor sources, multiple subsystems, or multiple stages. Models of the operator's information handling task performance would be of use both in describing the interaction between operator and system and in predicting the performance gains to be expected from the introduction of varying levels of computer aiding. Further, in situations in which the responsibilities for some task are shared by other crew members or by an automated decision maker, these models might also be used within the system to coordinate the actions among the decision makers.

In general, two types of models have been used for performance prediction purposes. One type of model that describes what the operator does. This is referred to as a behavior model. Another type of model that describes how well the task is performed, and is termed a performance model. Since the decisions involved in the process need to be judged by both subjective and objective factors, we believe that a simple performance model alone will not be adequate to provide satisfactory prediction. Rather, a detailed behavior model is required that can accurately predict behavior, and in turn be able to accurately predict performance.

Within behavior models, there are two general approaches. Descriptive modeling is designed to describe actual rather than optimal behavior, whereas prescriptive modeling prescribes optimal behavior according to some set criteria. As rational, effective behavior of operator is the main concern, the use of prescriptive models is more appropriate.

Prescriptive models are often based on optimization of underlying descriptive models. These models include control and estimation approaches, process interaction approaches, and knowledge-based approaches. A number of models of the human operator as controller and observer have been developed. Surveys of these approaches can be found in Govindaraj (1979) and Rouse (1980). The state-space control theory models are best used for situations when controlling or monitoring the control processes is the primary objective.

Closely related estimation theory models have been used in failure detection of continuous processes. Both approaches find good applications in the lowest level of supervisory control behavior: scanning, acquisition, and tracking; maneuvering, regulating and trimming; where the operator finds continuous interaction with the system.

Within process interaction approches, we include network models, multiple-stage programming approach, and queueing models, etc., which involve task breakdown into decision subprocess and decision epochs (using the terms of "event," "stage," or "node and branch"). The SAINT technique (Systems Analysis of Integrated Networks of Tasks, Seifert and Chubb, 1978) is a notable example for the realization of network model. These models provide the ability and felixibility to combine models of dynamics (e.g., aircraft equation of motion) with models of discrete sequences (e.g., operator actions). The SAINT model consists of a network of nodes and branches of subtasks that are described by a set of characteristics (e.g., performance time duration, priority, resource requirements). This simulation technique provides the system engineers the opportunity to analyze system effectiveness and quantify the relative contributions of human and machine.

Dynamic programming approach and Markovian decision model (Howard, 1960; Hammer and Rouse, 1979) provide suitable analytic framework for "key-stroke" level description and recurrent multi-stage decision process. A review of multi-stage decision model is given by Krishna-Rao and Kleinman (1979). However, the approaches are computationally plagued by the "curse of dimen-sionality" for global holistic evaluation. Hence, assumptions are usually made to simplify the computational procedures, or alternative solution pro-cedures are implemented (e.g., Tulga and Sheridan, 1980). If only global description of activities and gross estimates of performance are required from the model, the queueing theory approach seems to be a suitable alter-native for modeling time-variant information processing and decision-making behaviors.

Knowledge-based systems have been used to automate some high level, discrete planning and information seeking processes (Wesson, 1977, Goldstein and Grimson, 1977) where the situation-action pairs were defined for each distinct environmental condition. Examples of such discrete productions in an air traffic control task (Wesson, 1977) and a tactical mission planning situation (Engelman, Berg, and Bischoff, 1979) are shown in Figure 2-2. Control systems are used to decide which rule-sets to fire in a given situation, how to resolve conflicts in several rule antecedents and how to sequence the resoluting actions.

With varied types of modeling approaches as shown above, proper selection of the underlying descriptive model probably should be based on the context of task such as the level in supervisory control hierarchy described in earlier sections, and the characteristics of the task demand. The point, according to Rouse and Johannsen (1979), is that:

> There are limits to context-free analytical modeling. First, there is the very important idea that human behavior mainly reflects the task environment. Thus, searching for a specific analytical model of general human behavior may only be fruitful to the extent that all task environments are common. Perhaps then one should first search for commonality among environments rather than intrinsic human characteristics. In other words, a good model of the demands of the environment may allow a reasonable initial prediction of human performance.

It then becomes clear why optimal control and observer models exhibit success in modeling lowest-level, supervisory control, i.e., monitoring and execution. These approaches will be discussed in the next section.

2.4.2 <u>Approaches to Modeling Monitoring and Execution Task</u>. Task analyses of advanced aircraft operation have shown the increasing importance of monitoring and execution functions. Along with the continued

```
A.  Separation conflict ━━━▶ try climbing
                             try descending
                             try turning right
                             try turning left
                             try slowing down
                             try holding


B.  Too high for approach handoff ━━━▶ descend


C.  Off track ━━━▶ try turning back to track
                   try next radio fix
                   try doing nothing
```
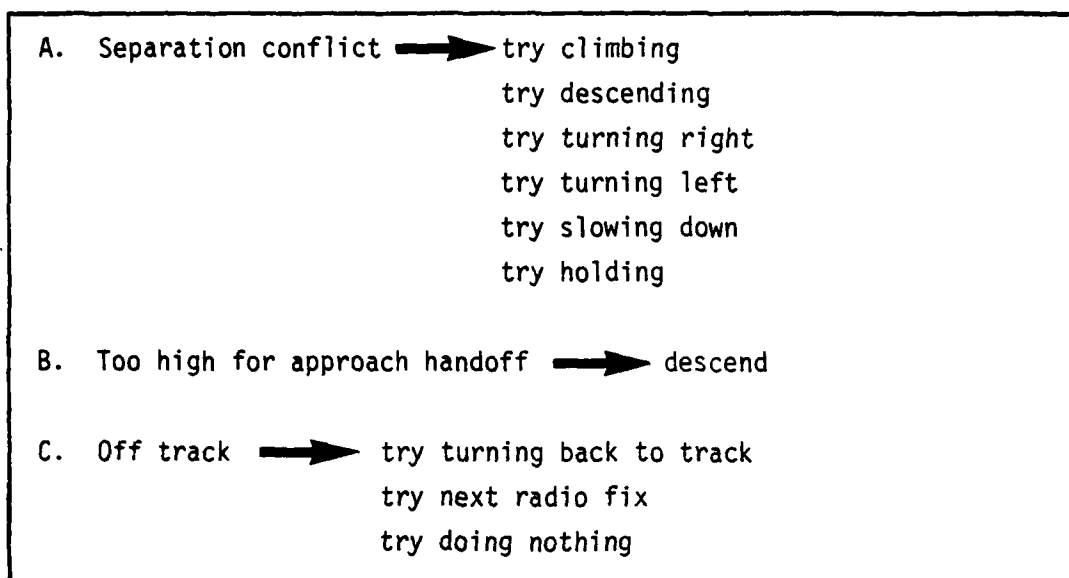
(a) Example productions in air traffic control   (Wesson, 1977)

```
    IF                                                    ˎ

    1:  THE target is PINPOINT
AND 2:  THE CLOUD COVER OF THE target
        IS LESS THAN 2/8
AND 3:  THE time on target IS WITHIN DAYTIME
AND 4:  THE AAA DEFENSE OF THE target
        IS MORE THAN LIGHT
AND 5:  PAVE KNIFE IS AVAILABLE AT time on target


                    ━━━▶ THE BEST MUNITIONS FOR THE target IS
                         ONE OF:  MK-82-LG, MK-83-LG, MK-84-LG
```
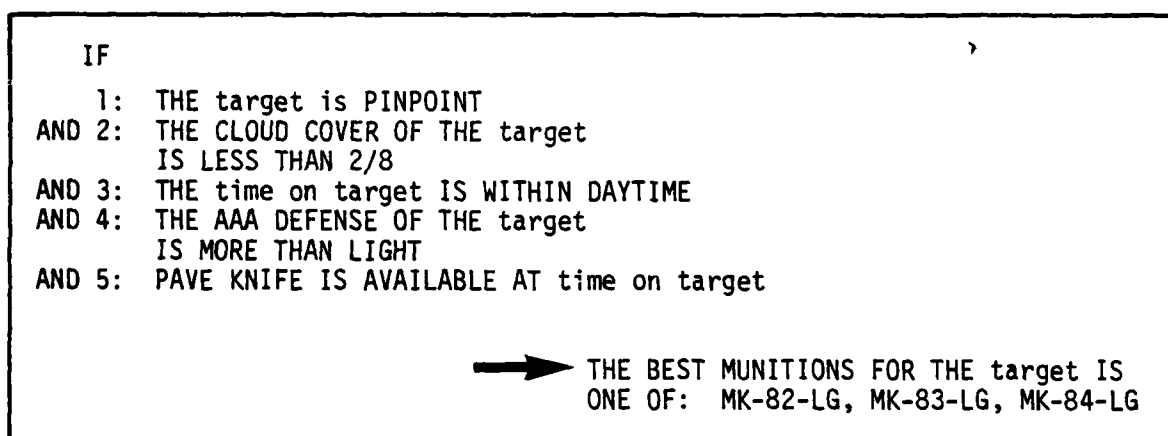
(b) Example tactical air mission planning system   (Engelman, Berg,
                                                         Bischoff, 1979)

FIGURE 2-2.
(a) EXAMPLE PRODUCTIONS IN AIR TRAFFIC CONTROL
(b) TACTICAL AIR MISSION PLANNING

trend of airborne automation in man-machine systems, the dimensions of operator activities as a monitor and supervisor increase. As a result, new modeling requirements of operator performance evolve. A set of new requirements for a theory of man-machine systems has been proposed by Funk and Miller (1979). Based on their suggestions, a model of operator monitoring/execution task should:

(1) Recognize that human operators perform a variety of tasks including control, monitoring, supervision, decision making, detection and many others.

(2) Allow the description of tasks as collections of procedures at any appropriate level of abstraction.

(3) Recognize the presence of multiple, prioritized, serial and parallel tasks.

(4) Consider the presence of multiple human operators, treating single operator systems as special cases.

(5) Deal with the concepts of communication and coordination of people, machines, and activities.

(6) Make provision for appropriate description of automation.

(7) Include goals and subgoals as basic concepts.

(8) Include the concept of a man-machine system's knowledge base.

In recognizing these requirements, a considerable amount of research effort has been directed at understanding the human operator in multi-task, supervisory control situations. One general approach is to start with control theory from a general perspective that includes control with respect to continuous events as well as discrete events. This approach is represented by Muralidharan and Baron (1979), Govindaraj and Rouse (1979), Krishna-Rao and Ephrath and Kleinman (1979).

Muralidharan and Baron (1979) have studied supervisory control in supervising multiple, remotely piloted vehicles (RPVs). The operator has to choose which RPV to monitor and whether or not to intervene with discrete corrective control actions based on the vehicle's lateral deviations. Muralidharan and Baron's model is an extension of the optimal control model of the operator derived by infusing decision theoretic notions into control criteria. The model has been employed to study the effects of error tolerance and the number of RFVs per operator on overall system performance in terms of timing errors and deviations from the desired trajectory.

Govindaraj and Rouse (1979) have studied intermittent control with a preview of map displays for flight management. In such a case, the operator must divide his attention between control and discrete tasks. An analytical model is developed based on optimal control theory. The approach is characterized by differential weights in the cost functional, and a few threshold and limits. The model performs the discrete control task whenever the perceived error exceeds certain bounds, as it matches to the operator's behavior.

Krishna-Rao, Ephrath and Kleinman (1979) have sought to "transform" the optimal control model into an optimal decision model that is suitable for the multi-task situation where tasks of different value, time requirements, and deadlines compete for the operator's attention. The model, bearing conceptual similarity to the optimal control model, consists of two separate blocks: information processor and decision processor. The information-processor block divides the estimates of the "decision state," i.e., the amount of time required and the amount of time allowed to complete each task. These estimates, along with task values under subjective expected utility framework provide the selection of a task in the decision-processor block. The approach is quite general and suitable for discrete task dynamics.

Another approach, apart from general state-space control theory points-of-view, is to start with task analysis or task-paradigm development, and then to identify the subprocesses and the interactions among them. Abstraction of the process dynamics and interaction then leads the way toward simulation techniques and models. This approach is represented by Seifert (1979), Baron et al. (1980), Sheridan and Tulga (1980, Greenstein (1979), and Chu and Rouse (1979).

Seifert (1979) has proposed a combined SAINT discrete network model with an optimal control model formulation. The objective is to realistically examine and model an advanced man-machine system in which both discrete tasks and continuous tracking behaviors are exhibited. The mutual interaction between discrete tasks and continuous state variables is achieved through "mix-initiation," i.e., either by tasks being completed or by state variables crossing specific threshold values. The feasibility of employing this modeling approach has been demonstrated in a combined flight control with multifunction keyboard tasks in the Digital Avionic Information System.

Baron, Zacharias, Muralidharan and Lancraft (1980) have studied flight crew procedures in approach to landing. A simulation model based on time-line analysis of nominal procedures was developed. Their approach draws heavily on the concepts and submodels of the optimal control model for the human operator. The overall model structure, however, is one of subprocess interaction.

Tulga and Sheridan (1980) developed a multi-task, supervisory control paradigm and a dynamic programming model of monitoring and control behavior. The paradigm addressed is one of allocating in time a limited attention resource to multiple simultaneous demands of varying duration, production rate, and rewards. The model, embedding several criterion functions and including response time and future discount constraints,

allows one to explore the interacting factors of task demands, operator's "plan-ahead" behavior, and task parameter estimation on the performance of multiple-process supervision.

Greenstein, (1979) has considered the operator's monitoring of multiple displays of stochastic processes. A two-stage model that represents the operator's event detection task and attention allocation task is developed. In the first stage, a discriminant analysis technique is used to model the operator's generation of probability estimates that events have occurred after the observation of display. In the second stage, action times and delay costs, along with the event probabilities, are used in the queueing framework to determine the order of tasks to be attended.

Chu and Rouse (1979) considered human-operator interaction in the multi-task, flight management situation. Allocation of responsibility between operator and computer is modeled as a control process of the queueing system. It was proposed and demonstrated in the study that the operator's workload can be maintained within an acceptable level, if routing of information handling responsibility (such as check-list procedure) between operator and computer can be achieved and adapted to task demand. Since this control of information flow concept will further be elaborated in our program study, a review of queueing theory modeling concept will be given in the next section.

2.4.3 <u>Information Handling as a Queueing System</u>. The information flow concept derived in this study is based on pragmatic information value and multiprocessing organization. The former notion refers to the assumptions of the close interrelationship between information and decision and the abilities of the operator to quantify and compare information (Whittemore and Yovits, 1973). The later notion refers to the use of analogy of time-shared computer in viewing operator's attention allo-

cation among a variety of tasks (Johannson and Rouse, 1979). If one is concerned with time performance and productivity (i.e., throughput), the queueing theory may be an appropriate formulation. The following paragraphs will briefly describe the earlier work using queueing formulation. A review of queueing theory and a survey of queueing model in multiple task man-machine systems can be found in Rouse (1980).

Descriptive Queueing Models. A model for the instrument monitoring behavior of a human operator is provided by Senders (1964). The operator is assumed to use his limited input capacity to sequentially observe a number of instruments. An information theory approach is employed to determine how often and for what duration the operator must sample each display. For any instrument, the demand for attention depends on the bandwidth of the displayed signal and the precision required of the reading. Workload imposed by the instruments is calculated as the fraction of time spent observing them.

Smallwood (1967) has also modeled human information monitoring in multiple-process tasks. He proposed that the human operator forms an internal model of the processes he is monitoring and of the environments relevant to his task as a result of his past perceptions of them. Based on this internal model, probabilities of exceeding instrument threshold are estimated and the operator's attention is directed toward the instrument with the highest probability.

Carbonell (1966) provides a queueing theory model to explain the instrument monitoring behavior. He uses priority queueing discipline, in assuming that the human operator attempts to minimize the risk involved in not observing other instruments when he chooses to monitor a particular instrument.

Senders and Posner (1976), instead, employ a first-come-first-serve service discipline in modeling human information processing in multiple process monitoring tasks. They suggest two models of inter-observation interval (i.e., the time between physical presence to mental presence of an event). The first model involves the probability that the display variable will exceed an acceptable limit, much like the models used by Carbonell and Smallwood. The second model involves the degree of the operator's uncertainty about the value of the variable displayed on the instrument.

Rouse (1977) and Walden and Rouse (1978) have modeled the pilot in multi-task flight management situation as a "server" in a queue where events are the control and check-list procedure tasks. The events are assumed to arrive for service with exponentially distributed inter-arrival time, and serviced according to their priority. The "arrival rate" for control tasks was measured from experimental results for control activities, and the service rate was determined as a free parameter of the model. The model performance (mainly waiting time statistics) matches well with the experimental data.

All the above models work on the gross level of description in information handling. A queueing network model at the micro-structural level may prove useful. Before such a detailed time-shared central-processing model can be developed, all the gross level model may be considered as an aggregated representation of underlying processes. Often, such an approximated representation can provide a reasonably accurate and inexpensive prediction (Sauer and Chandy, 1980).

Control of Queue Approaches. Given the information handling situation characterized as queueing system, questions of interest arise. These are concerned with defining and quantifying the state of the flight crew, computer-display information system, and then determining how to schedule

or present the information message to the flight crew. This involves the control of information queue.

Using a queueing system framework, Markov decision processes have been employed by many researchers to represent queueing control problems. A review of the literature with emphasis on the dynamic control of queues using service variables, arrival variables, and priority discipline is given by Chu (1976). Therefore, only a brief overview is given below.

In the case of controls on service variables, possible strategies include (1) operator accepting or rejecting the event at service completion or at event arrival, and (2) operator selecting from a set of the allowable service rates at event arrivals or at service completion. In the case of controls on arrival variables, possible strategies include (1) operator varying the arrival rate from normal level to zero level, (2) optimal queue formation based on dynamic (state-dependent) discipline of assigning arrivals to the service channel that minimize overall cost, and (3) system varying the arrival rate from normal level at zero level.

In the case of priority control, the strategies involve the assignment of events to priority classes, or the natural set of classes given the determination of the service discipline. Within fixed priority classes, Cox and Smith (1961) have obtained an optimal priority assignment policy: of all the possible nonpreemptive, work-conserving, stationary policies, the head-of-the-line discipline with the highest priority assigned to the class of events with the highest service rate-waiting cost products is that which minimizes the average waiting cost. The result has been utilized in many simple priority models, which often serve as a guide for complex models. There are quite a few strategies that utilize dynamic priority including those of time-varying nature (Jackson, 1965; Kleinrock 1967) and those of a state-dependent nature (Mova and Ponomarenko, 1974; Heyman, 1968; Bell, 1973).

Utilizing a state-dependent priority control, Chu and Rouse (1979) have proposed an adaptive allocation of decision making responsibility between pilot and computer in multi-task flight management situations. A queueing theory formulation of multi-task decision making is used and a threshold policy for turning computer on/off is proposed. An experiment was conducted with different task demands and aiding levels. It was found that computer-aiding based on a dynamic priority control discipline enhanced both time performance and subjective ratings.

As has been shown in this survey of the control of queueing systems, the queueing approach is a handy and powerful tool for modeling a decision and control process. Several issues concerning the implementation of the queueing model are discussed in the following paragraphs.

The issue of uncertain information of system parameters such as the arrival rates or service rates has been overlooked and seems to be a promising area for further research. Most well-established queueing control policies seem to be vulnerable at this point. Exceptions are given in the previous survey (Chu, 1976) which has addressed various aspects of this issue. One major and promising approach to this problem is demonstrated by Bagchi and Cunningham (1972). They show how a statistical decision theory approach may be gainfully applied to handle the uncertainty of parameters such as the customer arrival rates pertaining to the optimal design of queueing systems. To reiterate the importance of the arrival and service information, an example is given in a study performed by Bar-shalom and Marcus (1980) in multi-target tracking with measurement of uncertain origin. Their study indicates that the probabilistic data association use time-of-arrival information is significantly superior to those that use only measurement location information.

Concerning the use of service information and preemption, one might expect to do a better job if one has better information about the likely process-

ing time of a job or if one is allowed to preempt a job which is in process. A survey of the analytical results in scheduling under uncertainty, appears to show that the optimal nonpreemptive sequencing strategy for linear costs is to employ the FCFS disciplines under no information situations and to employ the SPT disciplines under full or partial information.* In the preemptive situation the SRPT (shortest remaining processing time first) disciplines are employed in substitution for the SPT for the system to be optimal.

Finally, the important issue of information value, the process of weighing probable payoffs of a specific strategy to the decision against costs of acquiring the information has not been taken into account in all the previous work reviewed. Most models have used the simple waiting time cost and switching time cost alone. To compensate for this deficiency, a combined MAU and Queueing model will be explored in the next chapter.

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* FCFS stands for first-come-first-serve, while SPT stands for shortest-processing-time-first.

3. INFORMATION EVALUATION AND PROCESS MODELS FOR SUPERVISORY CONTROL

3.1 Overview

Analysis of the supervisory oeprator's information needs described in the previous chapter has supported the needs for modeling the subjective recurrent decisions of selecting information sources (i.e., the taxon aspect of information handling). A particularly attractive approach is one that incorporates the key factors--aircraft state, environmental conditions, operator capabilities, acquisition costs, etc.--into a multi-attribute decision model. This individualized model of information seeking policy has been found to be useful for evaluating alternative information system configurations and for automating taxon portions of the information handling task. The models have, for simplicity, been time-invariant and driven by paced events. The decisions have been undiscriminatly triggered by sensing of an environmental obstacle or threat. The model then selects the most effective information source for dealing with the unequivocal event.

Information seeking in advanced aircraft also concerns the sequencing of information handling, especially when there are a number of continuous processes--supervision of subsystems, communications, aerodynamic surfaces and multiple threats, etc. Many of these time continuous processes can be considered as queues of consciousness events, which are responsible for pilot decisions. Even the most complicated procedures in information handling can then be modeled as a network of sequences that as a whole guides the information flow from system to operator. The control-of-queue approach is best suited for describing the information sequencing (i.e., multiplexing) in multiple-information situations.

The approach presented in this chapter expands the previous time-invariant, event-paced information value model into the operational domains of time-varying information characteristics and sporadic event occurrence. Here the

time distributions of physical events such as system faults, course errors, and threat assessment can be estimated, and the probabilities of false alarm and miss event are assumed. The process model embedded in the queueing framework provides all the necessary updates of subjective and objective information value estimates, including the build-up in uncertainty regarding unattended events. The multi-attribute decision model is then incorporated as a criterion function in the control of the queue. The combined MAU/ queueing model will be particularly useful in depicting the operator's continuous monitoring and control functions. Also the whole spectrum of information handling tasks ranging from situation assessment to intermittent control can be represented as variations of process parameters such as event arrival rate, process rate, number of processing stages, etc. A rich set of behaviors can then be modeled and aided. The sections that follow will first review selected features to be used in the MAU model-based aiding, trace the development and validation of the adaptive modeling concepts (Section 3.2); present the continuous decision and control modeling concepts, derive the MAU/queueing model (Section 3.3); and summarize the related behavioral issues in computer-aided information handling for future investigation (Section 3.4).

3.2   Use of Multi-Attribute Utility Models for Adaptive Estimation of Information

3.2.1   Background. The genesis of the current program lies in a previous three-year program (Steeb, Chen and Freedy, 1977; Steeb, Davis, Alperovitch, and Freedy, 1978; Steeb, Chu, Clark, Alperovitch and Freedy, 1979). This earlier program resulted in the development and demonstration of a methodology for adaptive estimation of information value parameters and in the application of the techniques to modeling and aiding information selection behavior. The methodology is based on the use of multi-attribute utility theory to organize the various objective and subjective factors which enter

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into the taxon information decision. The adaptive nature of the program derives from the use of a training algorithm based on pattern recognition techniques to derive certain of the model parameters.

This section traces the structuring of an adaptive information-seeking model within a general multi-attribute utility framework: definition of the attribute set, determination of model form, specification of attribute levels and estimation of importance weights, and development of model-based aiding. The section ends with a description of the experimental demonstrations of the methodology.

3.2.2 <u>Factor Choice</u>. The multi-attribute decision model of information seeking behavior is based on a weighted aggregation of the factors which enter into a decision. In its simplest form the aggregation is a linear additive model:

$$\text{MAU}(a_k) = \sum_{\substack{\text{attributes} \\ i}} K_i U_i (X_{ik})$$

where
$$X_{ij} = \sum_{\substack{\text{states} \\ k}} P(z_k) X_{ijk}$$

where   MAU (a_k) is the aggregate utility of action k
        k_i is the importance weight of attribute i
        x_{ij} is the level of attribute i associated with action j
        $P(z_k)$ is the probability of occurrence of state z

The choice of factors or attributes in this model is extremely important. It was noted in our initial study (Steeb, Chen and Freedy, 1977) that the attribute set should be accessible, monotonic, independent, complete and

meaningful. Also, a single set must account for both information acquisition and action selection behavior. Finally, the attribute set must be manageably small in dimension. With these considerations in mind, an initial taxonomy of consequences can be organized around the following five areas:

(1) Communication costs--such as energy, equipment, and attention.
(2) Equipment attrition--fuel expenditures, vehicle damage, etc.
(3) Objectives attainment--area reconnoitered, payload delivered.
(4) Dynamic effects--effects on availability of future information and on system capabilities.
(5) Subjective factors--preferences regarding control continuity, operator load.

3.2.3 <u>Attribute Level Determination</u>. The level or quantity of each attribute for a given outcome can be determined in several ways. For example, mappings between predictive features and the attributes can be established by observation and adjustment. Here, data available to the decision program concerning the environmental state, vehicle state, channel characteristics, sensor capabilities, and operator load can be used to predict the attribute levels. Alternatively, the attribute levels may be estimated subjectively or established from performance histories. Use of mappings from predictive features is more attractive than subjective estimates as no load is imposed on the operator, and situation-specific factors may be taken into account. For example, the communication delay may be directly predicted from sensor queue length, sensor response characteristics, and transmission distance. Subjective estimates or pre-established values for the attribute levels would tend to be much less reliable than such in-task calculations.

3.2.4 <u>Attribute Weight Estimation</u>. The policy defining factors in the model, the importance weights k_i, are parameters suitable for either objective or subjective estimation. If the consequences can be defined along

objective scales (dollars, ship-equivalents, etc.), then the weights could
be derived by analysis and input prior to system operation. Unfortunately,
Felson (1975) states that only in a few highly structured situations can
such an optimal model be derived. More often, the operator's goal structure,
expressed as importance weights, must be elicited or inferred and then incor-
porated in the model. There are a number of advantages to such subjective
estimation, particularly with respect to allocation of function. By incor-
porating individualized operator weights in the model, the complex evalua-
tion and goal direction functions remain the responsibility of the operator,
while the normative aggregation functions are assumed by the computer.
Also, operator acceptance of aiding by the model may be increased since
individual preferences are incorporated in the machine decisions.

The operator's subjective weights may be defined off-line by elicitation or
on-line through inference. The off-line methods include direct elicitation
of preference, decomposition of complex gambles into hypothetical lotteries,
and use of multi-variate methods to analyze binary preference expressions.
These techniques are accurate and reliable in many circumstances, but they
have a number of disadvantages when applied to operational systems. Typi-
cally, these methods require two separate stages--assessment and application.
Assessment required an interruption of the task and elicitation of responses
to hypothetical choices. Problems arise with such procedures since the
operator's judgments may not transfer to the actual situation; the decision
maker may not be able to accurately verbalize a preference structure (Mac-
rimmon and Taylor, 1972); and the judgments made in multi-dimensional choices
are typically responses to non-generalizable extreme values (Keeney and
Sicherman, 1975).

Estimation techniques relying on inference from in-task behavior may be
more useful. The inference techniques can be based on non-parametric forms
of pattern recognition. Here a model of decision behavior is assumed and

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the parameters of the model are then fitted by observation and adjustment. Briefly, the technique developed considers the decision maker to respond to the characteristics of the various alternatives as patterns, classifying them according to preference. A linear discriminant function is used to predict the decision maker's choices, and when amiss, is adjusted using error correcting procedures. In this way, no preference ratings or complex hypothetical judgments are required of the operator.

The adaptive nature of the estimation program is shown in Figure 3-1. Expected consequence vectors associated with each information source are input to the model. These consequence vectors are dotted with the weight vector, resulting in evaluations along a single utility scale. The maximum utility choice is determined and compared with the operator's actual choice. If a discrepancy occurs, the weight vector is adjusted according to the following rule:

$$\underline{k}' = \underline{k} + \lambda(\underline{x}_c - \underline{x}_m)$$

where $\underline{k}'$ is the updated weight vector

$\underline{k}$ is the previous weight vector

λ is an adjustment constant

$\underline{x}_c$ is the attribute vector of the chosen alterantive

$\underline{x}_m$ is the mean attribute vector of all alternatives ranked by the model above the chosen alternative

Ideally, the error correction moves the weight vector in a direction minizing subsequent errors. The amount of movement depends on λ, the adjustment increment. Nilsson (1965) describes several different forms of λ that can be used depending on the combination of speed and smoothing desired.

The type of criteria used for mdoel training is also a major consideration. The training may be based on objective outcomes such as stock market

FIGURE 3-1.
ADAPTIVE ESTIMATION PROCESS

The figure shows the adaptive estimation process with the following labeled elements:

EXPECTED CONSEQUENCE VECTORS — ATTRIBUTE WEIGHT VECTOR — EVALUATION

INFO. SOURCE 1 → $[x_1 \; x_1' \; \ldots \; x_1^n]$ → K_1 → MAU_1

INFO. SOURCE 2 → $[x_2 \; x_2' \; \ldots \; x_2^n]$ → K_2 → MAU_2 → MAX

INFO. SOURCE m → $[x_m \; x_m' \; \ldots \; x_m^n]$ → K_m → MAU_m

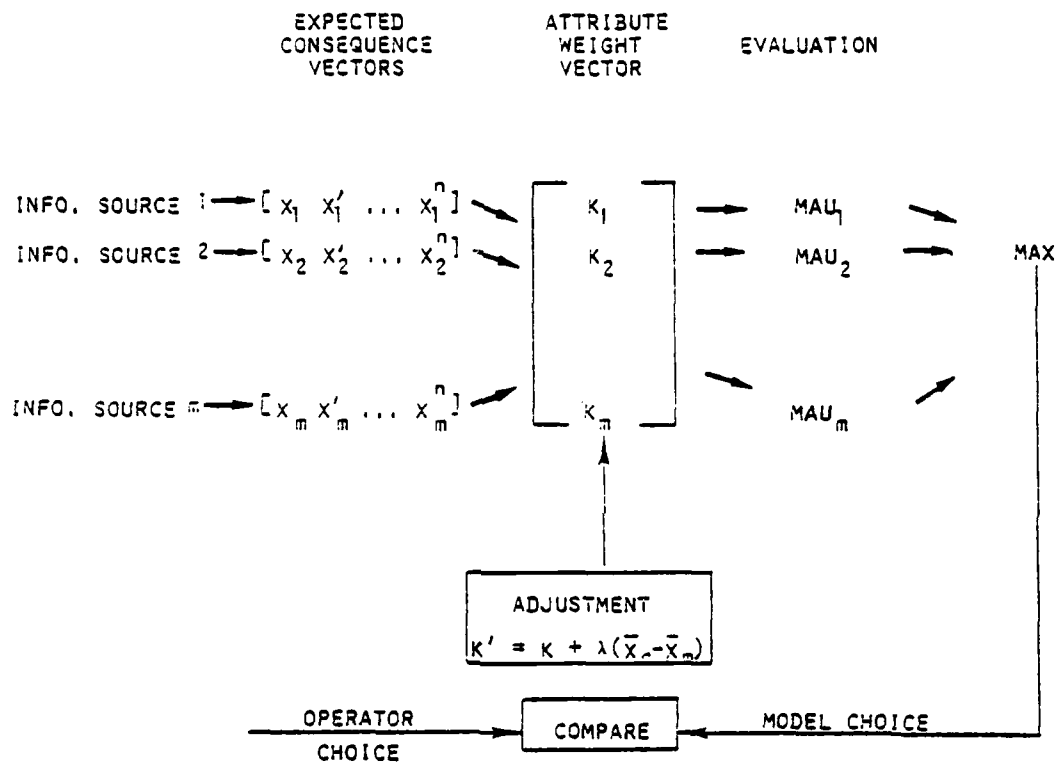ADJUSTMENT
$$K' = K + \lambda(\bar{X}_c - \bar{X}_m)$$

OPERATOR CHOICE → COMPARE ← MODEL CHOICE

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consequences, or subjective criteria such as actual operator decisions, or on some combination of subjective and objective criteria. The approach based on both objective and subjective criteria is the most involved.

In many situations, an occasional indicator of objective performance is observable. The aircraft may be lost, the target attained, or some number of subgoals accomplished. In this way, the correctness of a sequence of actions may become objectively known. The utility model would be trained subjectively prior to this by observation of the operator's choices. If the sequence of choices led to an objectively favorable outcome, the trained parameter set would be retained. If the outcome was unfavorable, the parameter set would be returned to the levels present prior to the sequence of decisions. In this way, objective criteria would guide overall training, but the explicit decision-by-criteria would guide overall training, but the explicit decision-by-decision policy for information management would be subjectively derived.

3.2.5 Automated Management of Information. The information value model described in Section 3.2.2 can be used directly for management of information. The multi-attribute utility model represents the policy of the specific user, it has access to the factors characterizing each information choice, and it can be linked to the onboard information control system. The model can thus be configured to automatically scan the available information sources, select the immediately most useful source, and display it to the operator.

3.2.6 Information Source Evaluation. Two types of evaluation are possible using the information extracted from the information value model: direct contribution and marginal contribution. Each of these evaluation measures is described below.

<u>Direct Contribution</u>. This is the user-specific value of a given information source in a given task situation. As such, it is a simple aggregation of components, weighted by the user's policy:

$$\text{info value }_{jks} = \sum_{\substack{\text{attributes} \\ i}} k_{ij}\, \bar{x}_{iks}$$

where info value $_{jks}$ is the aggregate value of source s to user j in situation k, k_{ij} is the importance weight of attribute i to user j; and $\bar{x}_{ijs}$ is the mean level of attribute i in situation k for source s. This formulation is useful when each information source contributes to a different task—threat detection, navigation, etc. The direct contribution measure does not deal with information sources having overlapping function. This situation requires use of marginal information value computations.

<u>Marginal Contribution</u>. In a group of information sources with overlapping function, the information value of one source can be calculated with the following expression:

$$\text{information value }_{jks} = \sum_{\substack{\text{attributes} \\ i}} k_{ij} x_{iks} \;-\; \max_{\substack{\text{over} \\ \text{remaining} \\ \text{sources}}} \sum_{i} k_{ij} x_{iks}$$

This is the incremental value of a source over the next most highly valued source. The summation of all positive contributions for a given source indicate the source's value in the particular task situation.

Using either the direct or marginal measure of information value, the mission value of an information source can be calculated as the summation across the probability distribution of task situations.

$$\text{info value}_{js} = \sum_k \text{prob (situation k)} \cdot \text{information value}_{jks}$$

This provides an overall, user-specific index of information value.

3.2.7 <u>Experimental Validation</u>. Evidence for the usefulness of the multi-attribute utility formulation and adaptive estimation programs was obtained during the initial year of the program (Steeb, Chen and Freedy, 1977). A simulation resembling control of a remotely piloted vehicle (RPV) was used in this study. Individual subjects navigated the RPV through a changing hazardous environment. In doing so, the operators selected different combinations of information and control allocation. The adaptive model was found to be significantly more predictive of subject's behavior than either a constant, unity weight model or an off-line method of weight estimation. Also, the model was found to be useful in identifying different decision policies or styles.

Use of the adaptive and off-line models to make choice recommendations to the operators had mixed results. The differences in task performance noted between the recommendation-aided and unaided conditions did not reach significance, although those who followed the recommendations most closely achieved the highest scores. Also, the adaptive model was found to be useful in identifying strategies which led to superior performance.

The second and third year efforts (Steeb, Davis, Alperovitch and Freedy, 1978; Steeb, Chu, Clark, Alperovitch and Freedy, 1979) built on the findings of the initial work by investigating the usefulness of the information value models for automating the presentation of information and for evaluating the effectiveness of information display configurations. These programs re-directed the application area from one of remotely piloted vehicle supervision to one of information selection in advanced aircraft. A simulation based on multiple threat intercept operations in advanced aircraft

was developed. Additional factors for time stress, decision complexity, resource limitations and as expanded information and action set were included in the new decision models.

The primary focus of these succeeding series of experiments was to test the effectiveness of the adaptive decision model for information management and information system evaluation. Subjects (a total of 20 in the studies) were required to select from a variety of forms of information regarding multiple, uncertain threats and to take aggressive or avoidance actions in response. The information options differed in cost, time delays, threat discrimination and enemy detection. The operators experienced a sequence of decisions organized into mission phases. Comparisons were made between (1) automated information management based on the adaptive model described earlier, (2) automated information management based on information seeking strategies elicited directly from the operator, and (3) manual information selection. Each subject experienced sessions of each of these conditions under low and high speed stress. Information management using either auto-mated form was found to result in improved task performance over manual selection. The improvement with aiding was enhanced in situations of high-speed stress. The performance score improvement with adaptively-based management over manual selection changed from 30 percent improvement in the low-speed stress conditions to 60 percent improvement in the high-speed stress conditions. Finally, the adaptive technique was found to be superior to direct policy elicitation, both for automated information management and as a basis for information system evaluation.

3.3   Integration of MAU and Queueing Models

3.3.1   Overview. The pilot in advanced aircraft is a primary example of man-machine systems in which the operator's role is changing from that of

a continuous controller to that of a monitor. In general, concurrent
information demands* are imposed on the pilot by display or by real events.
Consideration of the information requires a response (decision) from the
operator which is specified by the task information. For the design of
such man-machine systems, i.e., of their dynamic properties, display and
control, and computer-aided decision making, the operator strategies in
dispatching concurrent information demands have to be described by means of
both analytical models and experimental investigations. Notions of queueing
theory are suitable for the formulation of operator in multi-task situation
(Rouse, 1930; Chu and Rouse, 1979; Greenstein, 1979; Govindaraj, 1979; Rouse,
1977; and Carbonell, 1966). This is because unlike estimation and control
theory which are concerned with system performance as defined by deviations
from desired trajectory, the queueing performance measure can include the
time delay of processing as well as the time-line task loading.

The adaptive MAU-based program discussed earlier handles the discrete choices
present in airborne operations, but does not deal with the many continuous
behaviors present in monitoring, tracking, etc. Many of these continuous
stochastic processes can be modeled by embedding the multi-attribute decision
model in a queueing model. Here the time distributions of processes such
as system faults, course errors and environmental threats are known, and a
queue of potential messages or sampling options are present. The queueing
model provides a descriptive framework to accommodate the build-up in un-
certainty regarding a given process. The multi-attribute decision model is
then incorporated as a criterion function in the queueing model. This
section describes the proposed interfacing of the two types of models and
the preliminary analytical results of the current year's study.

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*These concurrent demands may arise as a result of multiple targets in the
environment, multiple channels in the communications, multiple samples in
the sensors, multiple subsystems, multiple stages in the procedure, or some
other sporadic events.

3.3.2 <u>Continuous Decision and Control Model Requirements</u>. Task analyses of pilots in advanced aircraft have demonstrated the increasing importance of supervisory control functions, such as status appraisal, monitoring and system interaction. Typical examples of supervisory tasks are seen in tactical operations, flight control/navigation, and subsystem supervision. In tactical information handling tasks, status appraisals include both environmental (terrain, traffic and weather) and resource factors; monitoring includes target detection and identification; and information system interaction includes target acquisition, sensor adjustment and maneuver constraint checks. Similarly, in subsystem supervision, these three dimensions of information handling are represented by configuration and reserve (status appraisal); performance envelope, tolerance checks, and potential hardware failure (monitoring); and communication, clearance, back-up mode, and emergency (interaction). In view of the range of continuous supervisory tasks in advanced aircraft, the operator task model must provide predictability, sensitivity, compatibility and generality.

Among the operator task models of information handling that were reviewed in the previous chapter, the most relevant modeling concepts include that of Sander's (1964) visual sampling model, Smallwood's (1967) instrument monitoring model, Carbonell's (1968) queueing model of visual sampling, Doetsch's (1975) supervisory flight control concept, DAIS system concept (Aviation Week and Space Technology, 1979), SAINT network model (Kuperman, et al., 1977), Greening's (1978) crew/cockpit modeling survey, Rouse's (1978) airborne information management and Cavalli's (1978) discrete-time pilot model. These studies point out the emerging need for a general model for operator information handling tasks, which is capable of representing (1) stochastic aspects of information processing, (2) general top-down system organization and bottom-up system synthesis process using integrated display control, (3) discrete events of underlying continuous processes, (4) parallel and serial operations and (5) interactive control and display systems.

3.3.3 <u>Decision Tree Representation</u>. The previous year's studies of the information handling task in advanced aircraft operations have dealt exclusively with independent discrete decisions--tasks in which the possible information options are scanned, a set of options selected are observed, and an action taken. The more realistic but also more complex case is that of continuous supervisory function--the operator must monitor the *different continuous* stochastic processes on an intermittent basis and resume any actions required. A further elaboration will include the much more complex case of continued information sampling--the operator sequentially samples different sources until some confidence level is achieved prior to action execution. With these considerations in mind, a simplified decision tree shown in Figure 3-2 has been developed for the hypothetical scenario of combined multiple threat, navigation, and flight management operations. The first branching shows the implicit decision between continued status appraisal and detail information seeking. If the first option is chosen, the top level information is displayed and no immediate action is required. If the second option is chosen, the information sources regarding *threat, navigation and subsystem are* unfolded for the operator's explicit selection. The MAU model discussed earlier will be used to evaluate all explicit selection processes, while the implicit selection processes present in the operator's mind will be modeled using a queueing framework to be discussed in the coming section.

The MAU models make the information handling process goal directed, normative and axiometric. Instead of simply attempting to predict behavior on the basis of a set of separate features with different criteria, the utility model structure ties the information decisions direct to the ensuing action decisions. First, at the system process level, the value of obtaining information for a specific event is determined by its impact on the expected utilities of both the subsequent decision for the specific event and the indecision over all other events. Second, at the information source level, the information chosen for regarding a given event is assumed to change the
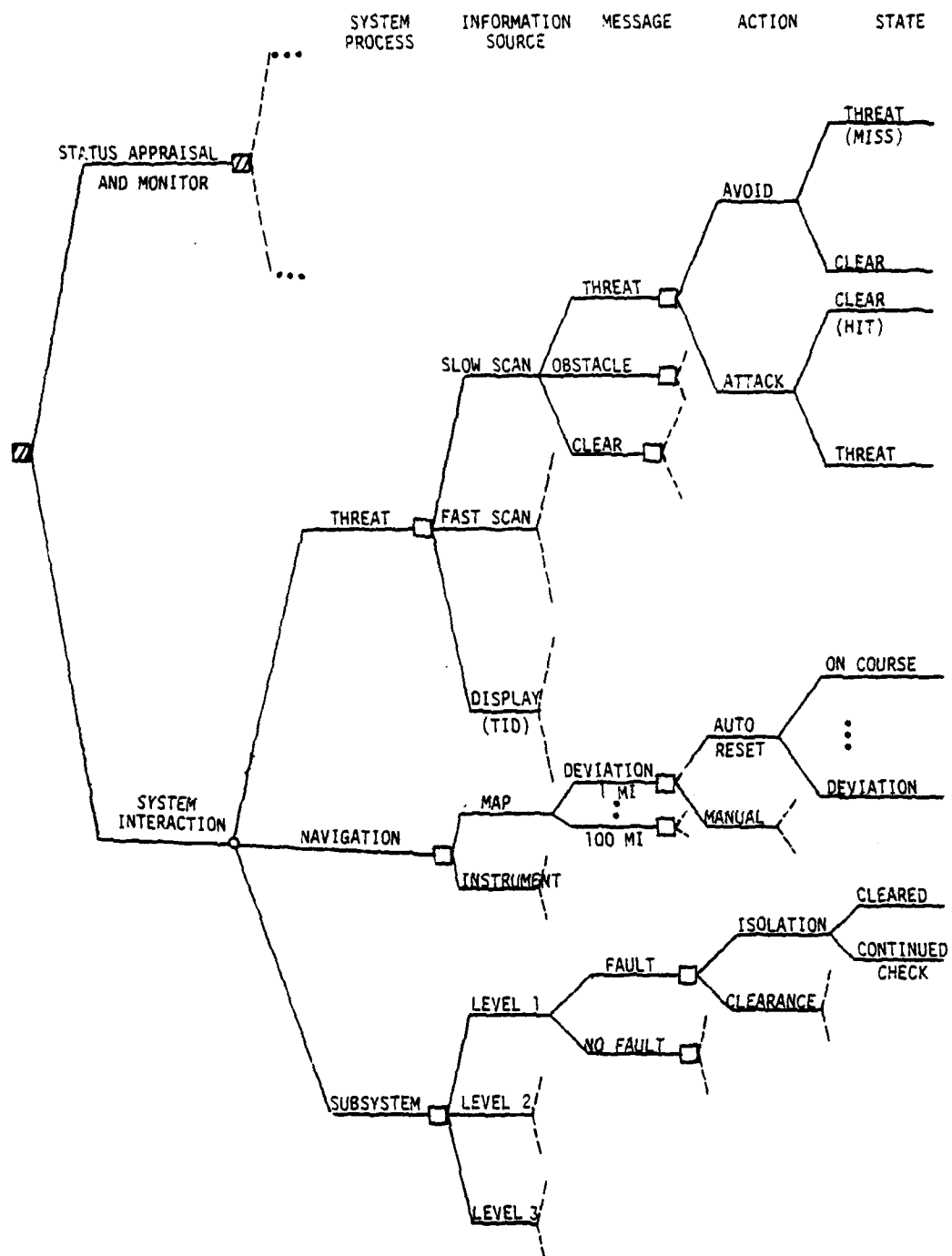
3-14

FIGURE 3-2.
TWO-LEVEL INFORMATION SELECTION DECISION TREE

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probability distributions of the specific event and the consequence sets, and, in turn, to revise the expected values of the alternative actions related to the specific event alone. All the consequence probabilities related to other events remain unchanged. Further down the tree is the message level, where the impact of data item is to change the probability distribution of the state. This expected utility decision analysis, championed by such researchers as Emery (1969), Marschak (1971) and Wendt (1969), is suited only for highly structured tasks. Also, although this is only a two-level information/action sequence, the decision space is fairly large, resulting from all possible combinations of message and action. It is then necessary to fold back the tree to associate each information source with the expected utility of the favored actions. This process will be elaborated in an example given in Section 3.3.5.

3.3.4 Event Flow. The queueing framework of operator/information process interaction is based on the continuous task flow concept described in Figure 3-3. This framework provides the linkage between the operator's cognitive functions such as event detection and attention allocation and the individual value functions for information processing. The framework assumes that the operator has sequentially or randomly monitored the process and has updated the estimates of event probabilities. Upon detecting or judging an event's arrival, the operator then places the event in memory or in a physical queue for attention. The atomic decisions actually involved in this information handling task are (1) monitoring or attending to a specific event, (2) selecting an event for attention, (3) selecting an information source, (4) continued information sampling/processing, (5) selecting an alternative event for action (if preemption is allowed) and (6) action selection. At the present stage of study, decision (1), (4), (5) and (6) will be prespecified and decisions (2) and (3) will be the main focus of the modeling effort. The usual practices related to decisions (1) and (4) are to attend a specific event if there is one and to continue information processing only when there is an incorrect response in information handling.
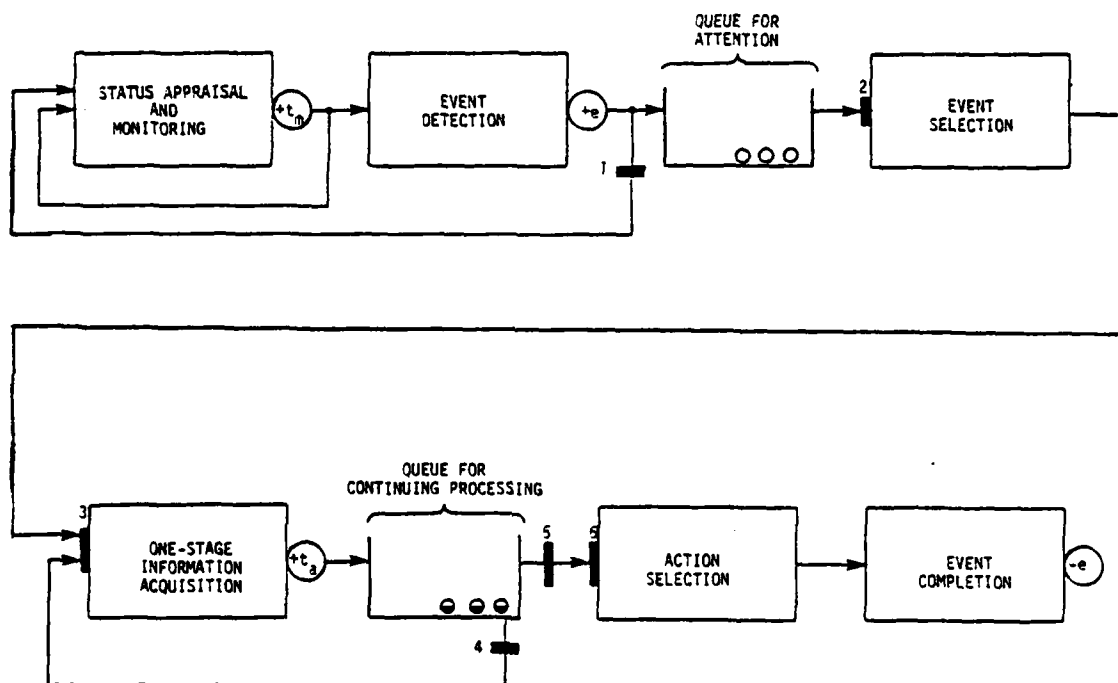
FIGURE 3-3.
INFORMATION HANDLING TASK FLOW DIAGRAM

Therefore, except for decision (5) which is determined by rules or strategies (e.g., preemptive, nonpremptive) all the prespecified decisions can be incorporated in a set of stochastic functions, such as probabilities of false alarm, incorrect response and missed event; and a set of probabilities for possible actions taken.

The next level-of-detail task description can be represented in a network of micro-transitions using the Petri net notation. Petri nets have been used in the study of parallel computation, multiprocessing, and computer systems modeling as well as the modeling human activities processes (e.g., Schumacher and Geiser, 1978). The following definition of Petri nets is from Miller (1973):

> A Petri net is a graphical representation with directed
> edges between two different types of nodes. A node repre-
> sented as a circle is called a place and a node represented
> as a bar is called a transition. The places in a Petri net
> have the capability of holding tokens. For a given transi-
> tion, those places that have edges directed into the transi-
> tion are called input places and those places having edges
> directed out of this transition are called output places
> for transition. If all the input places for a transition
> contain a token, then the transition is said to be active.
> An active transition may fire. The firing removes a token
> from each input place and puts a token on each output place.
> Thus a token in a place can be used in the firing of only
> one transition.

An example of the use of Petri nets is given in Figure 3-4, which simulates the internal information handling task flow shown in Figure 3-3, and the three concurrent processes each with multiple information choices shown in Figure 3-2. The network consists of two types of nodes, places P_i (represented by circles) and transitions of t_j (represented by bars). The dynamics of the network are represented by the movement of tokens (represented by black dots) which may fire mental state transitions. The diagram
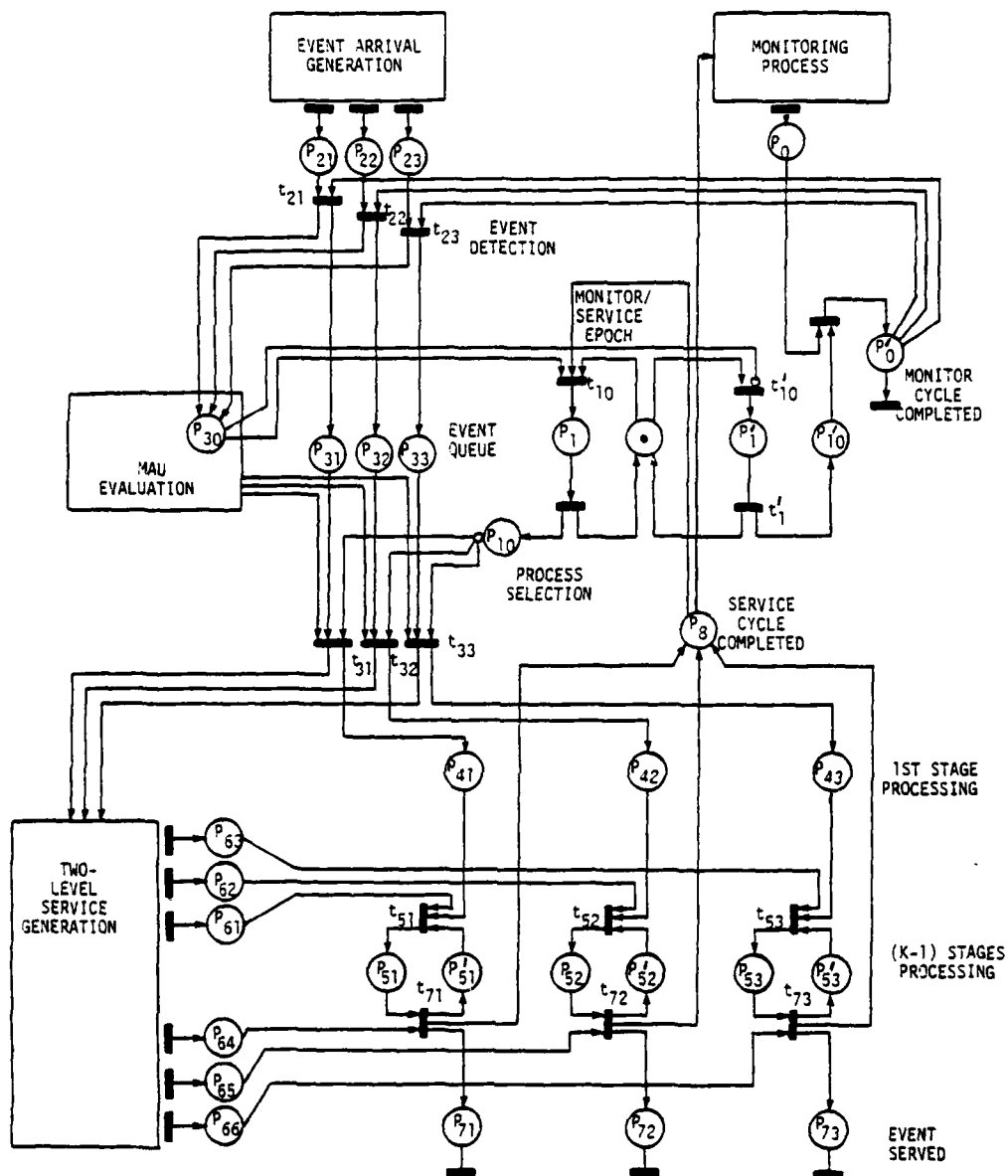
FIGURE 3-4.
NETWORK REPRESENTATION OF INFORMATION FLOW

illustrates those transitions between monitoring and detection (t_2), and those transitions between monitoring and handling (t_1). It also shows three logical steps of information handling: selection (t_3), first stage processing (i.e., acquisition, t_5) and follow-up processing (t_7). In order to model the rather consistent, cyclic monitoring strategy the pilot might use in concurrent with the automatic airborne sampling unit, Petri nets must be extended by including an inhibition arc (represented by an arc with a small circle instead of an arrowhead). An inhibition arc from place p_{30} to transition t_{10} enables the transition to fire only if the place p_{30} has no token in it, i.e., pilot monitors only if there is no event in the queue. Also augmented in the network are the time marking tokens at arrival, service, and monitoring which will enable the model to provide time information as well as event sequencing of the process.

The figure shows the fixed structure for a non-preemptive priority (NPRP) discipline applied both among the three processes and between monitoring and service. In the latter case, the event will only be detected and put into queue after the completion of monitoring cycle. The model also provides a framework for the computer simulation study (to be described in Section 4.2).

3.3.5 <u>Mathematical Formulation</u>. The proposed approach characterizes the information handling task as follows:

> (1) The information system processes N independent state (or feature) vectors.
>
> X_i, i = 1, 2, ..., N (System States)
> Y_i, i = 1, 2, ..., N (Observed States)

(2) The events e_i (the state or feature variations observed
   which call for information handling and response activities,
   such as check-list procedures, fault procedures, environment
   clearance, tactical maneuver, and threat estimates) arrive
   as independent stochastic processes with a priori probability
   density function (pdf) of:

$$f_i (\cdot) = f_i (\lambda_i), \quad i = 1, 2, \ldots, N$$

   where λ_i is the arrival rate of event i.

(3) The events e_i are detected or judged to "have arrived" after
   a monitoring epoch with the status display, with probability
   $P_i (\cdot | Y_i)$, the conditional probability of the event given the
   observed state.

(4) The prior statistics of information handling (service) time
   for event i using information j with state observation Y is
   given as:

$$g_{ij} (\cdot | Y) = g_{ij} (\mu_{ij}), \quad i = 1, 2, \ldots, N \qquad j = 1, 2, \ldots, J; \ J = \sum I_i,$$

   where $g_{ij} (\cdot | Y)$ is the pdf of service times t_s for observation
   Y, μ_{ij} is the mean service rate for given event i using informa-
   tion j.

Combined Monitoring and Event Execution. Given the above description, it
is useful to consider the strategy for combined monitoring and event execu-
tion, assuming that the information handling tasks are non-preemptive
(that is, the pilot is not allowed to attend another event before he finishes
the current one).

A classical queueing analysis which minimizes total system delay cost is:

$$E[c] = \sum_{i=1}^{N} c_i W_i$$

where c_i is unit cost of delay, and W_i is waiting time. This analysis results in the "μc" solution, which ranks the events according to the products $\mu_i c_i$.

There are several oversimpliciations to this solution. Among the major ones are: (1) it is difficult to translate multiple objective criteria of pilot decision into a pure cost per unit time delay; (2) it is not known that events arrive independently and unequivocally; and (3) the operator's observation of the arrival rate of λ_i and the use of a finite planning horizon may affect the accuracy of this solution. Nevertheless, the solution indicates that μ_i and c_i are important factors.

To take these issues into account, one considers the benefit of monitoring instead of execution in the presence of an event as follows: First, in the cases that the event unequivocally presents itself (that is, perfect dection, $P_i(e_i \mid Y_i) = 0$ or 1), the monitoring option represents the strategy of "sacrifice small wait, to catch big event." Second, monitoring also provides updated probability estimates as information is received when $0 < P_i(e_i \mid Y_i) < 1$. The benefit of this can be measured by reduced probabilities of false alarms and missed events.

It is especially important to note that if action a_i is performed, then subsystem m is ignored at the particular moment. The loss accruing due to this action is given by:

$$E[C_m \mid a_i] = p(e_m \mid Y_m) \int_0^{\infty} [t_a g_i(t_a) \cdot c_m] dt_a$$

$$+ [1-p(e_m|Y_m)] \int_0^\infty \int_0^{t_a} [(t_a - t)f_m(t)g_i(t_a)c_m] \, dt \, dt_a$$

where $f_m(\cdot)$ and $g_m(\cdot)$ are the pdf's for the arrival and service distributions, c_m is the unit delay cost for process m.

The first term in the righthand side of the equation above is the loss due to ignoring subsystem m for time t_a given that e_i has occurred. The second term is the loss that is expected to accure due to e_m occurring during t_a.

The total loss due to choice of action a_i is then:

$$E[C|a_i] = \sum_{\substack{m=1 \\ m \neq i}}^{N} E[C_m|a_i]$$

If it is assumed that c_i can be determined from expect payoff for optimized value selection from information j and action k, $E_{ik}[U_i]$, then following similar steps of Rouse and Greenstein (1976), the order of a_1 a_2 depends on the following performance relations (assuming Poisson arrival):

$$\frac{c_1}{c_2} = \frac{\text{Loss of delay to event 1}}{\text{Loss of delay to event 2}}$$

$$\frac{P(e_1|Y_1)}{P(e_2|Y_2)} = \frac{\text{A priori probability of event 1 given Y}}{\text{A priori probability of event 2 given Y}}$$

$$\frac{1 - e^{-\lambda_1 t_2}}{1 - e^{-\lambda_2 t_1}} = \frac{\text{Probability of event 1 arriving during action 2}}{\text{Probability of event 2 arriving during action 1}}$$

$$\frac{\lambda_2}{\lambda_1} = \frac{\text{Mean arrival time of event 1}}{\text{Mean arrival time of event 2}}$$

Incorporation of Multi-Attribute Criterion Function. The development to
this point has involved the use of a single-dimension loss functions. In
the context of supervisory control of advanced aircraft,multiple-objective
criterion function needs to be considered. The complete "state of nature"
is assumed to be characterized by the states related to threat, navigation,
and subsystem situations:

$$N = \{z_k\ (Z_t,\ Z_n,\ Z_s)\}$$

where Z_t, Z_n, Z_s are time-varying random state vectors.

The selection of process i and information type j at a particular time is
assumed to be based on the expected utility

$$\max_i\ \max_j\ [EU(e_{ij})]\quad i = 1, 2, 3, \ldots, N$$
$$j = 1, 2, \ldots, m_i$$

where $EU(e_{ij})$ is the utility of selecting information j with event i,

and
$$EU(e_{ij}) = \sum_k \sum_h P_i\ (O_h|I_j,\ z_k)\ U_i\ (O_h|I_j,\ z_k)$$

where

$P_i(O_h|I_j,\ z_k)$ and $U_i(O_h|I_j,\ z_k)$ are the probability and utility of
outcome O_h given information I_j and state z_k, $h = 1, 2, \ldots, H_i$,
$k = 1, 2, \ldots, K_i$.

If we let $MAU(e_{ij}) = \sum_{\ell=1}^{5} K_\ell\ X_{ij\ell}$, as suggested in Section 3.2, then the attribute
level $X_{ij\ell}$ is given by:

$$X_{ij\ell} = \sum_k \sum_k P_i\ (O_h\ |\ I_j,\ z_k)\cdot\tilde{U}_\ell\ (O_h\ |\ I_j,\ z_k)$$

where $\tilde{U}_\ell$ is the scaled utility of outcome on given information I_j and state z_k.

Multiple Threat and Flight Management Situation: An Example. Three classes of processes are defined as threat (TRT), navigation (NAV) and subsystem (SUB) processes. A plausible set of attributes ($\ell = 5$) is given by:

X_1 - loss or payoff with respect to threat process

X_2 - loss or payoff with respect to navigation process

X_3 - loss or payoff with respect to subsystem process

X_4 - information time expenditure

X_5 - information resource expenditure

And a set of outcome utilities is defined by

$\tilde{U}_\ell (Z_n) = \{$ U(avoid, U(damage), U(hit), U(miss) $\}$,

$\{$ U(NAV risk accrued/$_{\Delta t}$), U(NAV risk cleared),

U(SUB risk accrued/$_{\Delta t}$), U(SUB risk cleared) $\}$,

$\{$ U(TRT uncertainty accrued/$_{\Delta t}$), U(NAV uncertainty accrued/$_{\Delta t}$),

U(SUB uncertainty accrued/$_{\Delta t}$)$\}$

Then the attribute levels can be calculated as given below

$$X_{ij1} = R_1 - C_{12} - C_{13}$$

$$X_{ij2} = R_2 - C_{21} - C_{23}$$

$$X_{ij3} = R_3 - C_{31} - C_{32}$$

$X_{ij4} = 1/\mu_{ij}$, the mean information processing times

$X_{ij5} = cc_{ij}$, the communication costs

where R_i is the payoff associated with event i,

$$R_1 = P(a_1) \{ P(avoid|a_1, I_j) \, U(avoid) - P(damage|a_1, I_j) \cdot U(damage) \}$$

$$P(a_2) \{ P(hit|a_2, I_j) \, U(hit) - P(miss|a_2, I_j) \cdot U(miss) \}$$

$$R_\ell = U(\text{risk cleared on } \ell), \quad \ell = 2, 3$$

and C_{rs} is the expected cost accrued in process s due to the service of process r,

$$C_{rs} = P(e_s \mid Y_s) \cdot c_s \cdot \overline{t}_r$$

$$+ [1 - P(e_s \mid Y_s)] \cdot c_s \int_0^\infty \int_0^t (t - t_e) \, f_s(t_e) g_r(t) dt_e dt,$$

$\overline{t}_r$ is the mean service time of process r,

c_s is the risk accrued per unit time.

With Poisson arrival and Erlang service time distributions,

$$f_r(t) = \lambda_r e^{-\lambda_r t}$$

$$g_r(t) = \frac{(k_r \mu_r)^{k_r}}{(k_r - 1)!} \, t^{k_r - 1} \, e^{-k_r \mu_r t}$$

where λ_r and μ_r are the arrival rate and service rate and the k_r is the Erlang parameter of process r, it can be shown that

$$C_{rs} = P(e_s|Y_s) \cdot c_s \cdot \frac{1}{\mu_r} + [1-P(e_s|Y_s)] \cdot c_s \cdot$$

$$\{ \frac{1}{\mu_r} - \frac{1}{\lambda_s} + \frac{1}{\lambda_s} (\frac{k_r \mu_r}{\lambda_s + k_r \mu_r})^{k_r} \}$$

For $k_r = 1$, exponential service time distribution, the last term above becomes:

$$\{ \frac{1}{\mu_r} - \frac{1}{\lambda_s} + \frac{1}{\lambda_s} (\frac{\mu_r}{\lambda_s + \mu_r}) \}$$

Thus the expected cost accrued on process s due to the service of process r, C_{rs}, can be calculated as a function of λ_s, arrival rate, μ_r, service rate, c_s, risk rate, and $P(e_s|Y_s)$, event uncertainty.

3.3.6 <u>Combined MAU/Queueing Model Functions</u>. Summarizing this section, Figure 3-5 shows the functional block diagram of the combined MAU and queueing model for the shared man-computer information handling task. The information arrivals are generated from external information sources and transformed into a visual format (graphic, schematic, alphanumeric, symbol, or tones, etc.). Each new information arrival causes a reevaluation, and then a reformatting and a reordering of the information queue. The computation of infomration value is carried out by the MAU model according to the various formats and ordering sequences selected. The attribute levels and weights may be pre-assigned or estimated adaptively from the previous decision outcomes. At the present stage of development, a nonpreemptive priority scheme is assumed. More sophisticated schemes, such as the pre-emptive-resume priority and the control of queue for display based on predicted information load, will be implemented in the next phase of development. Issues of importance related to the aiding concepts based on this combined MAU/queueing model are discussed in the following sections.
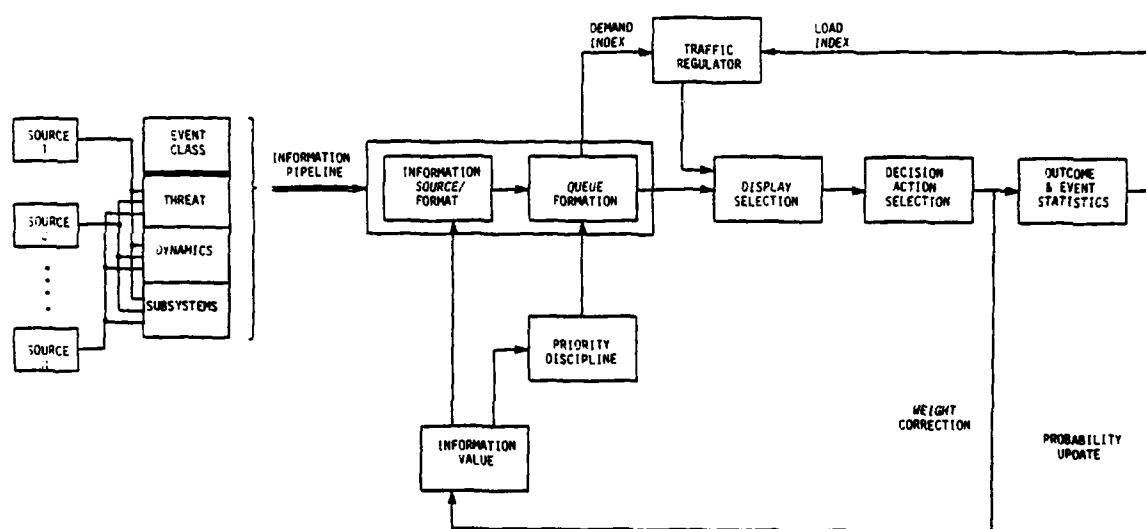
FIGURE 3-5.
FUNCTIONAL BLOCK DIAGRAM OF MAU/OUEUEING MODEL

3.4   Behavioral Issues

3.4.1   Operator Acceptance.   The combination of queueing and MAU-based
models described here has potential for significant aiding of the operator,
provided that the recommendations and automated functions are accepted.
Linear models based on the operator's observed behavior, using formulations
similar to that of the MAU criterion, typically outperform the operator
they are modeling (Bowman, 1963; Goldberg, 1970; Dawes and Corrigan; 1979).
Similarly, the queueing model prediction has the capability for relieving
the operator of complex monitoring, supervision and scheduling functions.
However, none of this is useful if the operator continually overrides or
otherwise disables the aiding system.

Potential resistance to the implementation of decision aids can derive from
many sources. Spector and his associates (1976) do a good job of summarizing
the major factors:

(1)   A decision aid may be perceived by officers as a threat to
      authority.
(2)   A decision aid may be seen as generating policy and decisions
      (decision automation) rather than acting merely as a guidance
      or planning tool (decision aiding).
(3)   A decision aid may lack practicality or realism because of
      improper or narrow focus and design.
(4)   A decision aid may simply be misunderstood, or training may
      be inadequate.
(5)   The algorithm that forms the framework of a decision aid may
      not be trusted or considered adequate.
(6)   All of the alternatives considered by a decision aid may not
      be displayed for the user, causing him to feel out of control.
(7)   A decision aid may lack the facility to be adapted to personal
      styles of problem solving or specific problem situations.

(8) Poor performance during an exercise may magnify and reinforce resistance to a decision aid.

In general, the research has demonstrated the need for development of a human-computer team rather than an automated decision maker (Hanes and Gebhard, 1966; Henke, Alden and Levie, 1972; Dawes, 1971). The human operator should always have the capability of controlling, through adjustment or override, the amount of aiding desired.

The acceptance of a decision aiding system that takes over much of the initiative for information management can be difficult to insure. A number of studies have shown that the utility of the aiding system in time-critical situations could be significantly increased if the aid did not require extra effort from the human to activate it (Steeb, et al., 1979; Chu, et al., 1979). The system then imposes no additional workload on the already overworked human operator. Cockpit environments have been used extensively in these studies, but other control environments also have received attention (Nuclear Regulatory Commission, 1979).

In general, the acceptance of a compter-based decision aid seems to rest on the following key factors:

Operator Load: This is the immediate decision load on the operator as evidenced by the speed and complexity of tasks being performed. As the operator load increases beyond a certain level, the value and acceptance of aiding has been found to increase (Hayes, 1964; Steeb, Davis, Alperovitch and Freedy, 1978; Verplank, 1977; Pasmooij, et al., 1976).

Model Confidence: The degree of confidence associated with the computer decision. Small changes in the accuracy or effectiveness of a computer aid can seriously affect its acceptance (Hanes and Gebhard, 1966; Halpin, Thorneberry, and Streufert, 1973; Halpin, Johnson and Thorneberry, 1974).

Decision Criticality: The extent and likelihood of major losses in the tactical situation. Operators may be unwilling to accept recommendations from or relinquish control to an aiding system in high risk situations (Hanes and Gebhard, 1966).

Perceived Control: The extent to which the operator understands and can influence the aiding process. Acceptance can be mediated by the operator's felt degree of knowledge and apparent degree of control. (Halpin, Johnson and Thorneberry, 1974; Steeb, Weltman, and Freedy, 1976.)

3.4.2 Confidence. One of the key indices used in selecting the model type and aiding form is the model confidence. This is the expected performance of the aiding system in the immediate situation. The measurable factors related to model confidence include:

(1) Model Training: The number of times the decision model has experienced the particular decision/situation pair. This may also be thought of as the newness of the situation.

(2) Estimated Probability of Success: The frequency of success of the aiding system in this particular situation. This frequency may be calculated from both passive and active aiding histories.

(3) Marginal Utility: The difference in expected utilities between the first and second ranked options. This indicates the "closeness" of the choice.

A combination of the second two factors, probability of success P(s) and marginal utility is favored. Accurate probability information is often not available, so that model training information may be used instead.

Display of the confidence is probably best accomplished using a multiple point scale. Display of the actual probability of success or training history is probably too fine a grade of information for effective assimilation. Also a threshold may be defined for confidence below which manual take-over is demanded and one above which automated control is unquestioned. Alerting displays may be associated with the two thresholds.

The sequence of training in a new situation illustrates the relationship of the aiding system function to confidence level. In the early stages of model training, the operator would be expected to perform the information management and vehicle control tasks, with the machine observing passively. If the operator required assistance, a default model could be invoked. As the machine training progressed, certain high confidence decisions could be recommended by the aiding system. With a plateau of training in a well-structured, consistent task, the new, confident aiding system could take over the bulk of the information management and control functions, subject to operator override.

3.4.3 <u>Operator Loading</u>. The task loading on the flight officer is expected to vary widely during a mission. The loading may be a result of decision complexity, the speed or frequency of decision-making or the number of tasks demanded of the operator. In some situations, the operator may manage to reduce information load by employing various handling strategies when over-load is expected. Strategies outlined by Meister (1976) include response selection, queueing, and omission; filtering of information to respond to fewer input dimensions; criterion modification which resuls in less response precision; and load balancing or time sharing between sources of input. In other situations, the operator can simply fail to cope with the more crucial phases of information handling for a decision. Hence, the results of excessive loading may be degraded decision making, "narrowing" to a sub-set of factors, inadequate response time, or the ignoring of certain pro-cesses. These suboptimal behaviors may be averted through use of several different forms of aiding:

(1) Changing the additive importance of time related factors (delay, speed, etc.) as the situation demands change.

(2) Providing greater amounts of unburdening through levels of automated information handling when the task complexity is excessive.

(3) Reducing display clutter by controlling information throughput at heavily loaded times through the use of a variable utility threshold.

A necessary precursor to implementation of any of these forms of aiding is the development of a methodology for measurement of immediate workload. A useful concept for the assessment of workload has been proposed by Jahns (1973). He divided the broad area of human operator load into three functionally related attributes:

(1) Input demand - factors or events external to the operator.

(2) Operator effort - internal to the operator.

(3) Performance - data outputs generated by the operator that serve as inputs to system components.

Some measurements of performance that fall into these categories are listed in Figure 3-6 (after Johannsen, 1976). The potential of various measures in predicting load has been discussed in an earlier report (Steeb, et al., 1979). More general surveys related to workload assessment can be found in Gartner and Murphy (1976), Moray (1979), and Williges and Wierwille (1979).

Measures of operator effort are of great concern and traditionally have been regarded as operator workload. One major purpose of a man-machine system modeling is to provide an accurate model of the human operator with predicted effort and performance as a function of the given task demand.

```
                          ┌ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┐      PROBABILITY OF ERROR
                          │      TIME LINE        │        TIME TO RESPOND
                          │      ANALYSES         │         RESPONSE CONSISTENCY
                          │ INFORMATION PROCESSING│          RESPONSE RANGE
        ENVIRONMENT       │      STUDIES          │           RESPONSE ACCURACY
          TASK/SITUATION  │  ACTIVATION-LEVEL     │             ETC.
            PROCEDURES    │     STUDIES           │
                          │        SUBJECTIVE     │
                          │     EFFORT RATINGS    │
     ┌──────────────┐     │ ┌────────────────┐    │     ┌──────────────┐
     │ TASK DEMAND  │─────┼▶│ OPERATOR EFFORT│────┼────▶│ PERFORMANCE  │
     └──────────────┘     │ └────────────────┘    │     └──────────────┘
                          └ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┘
```
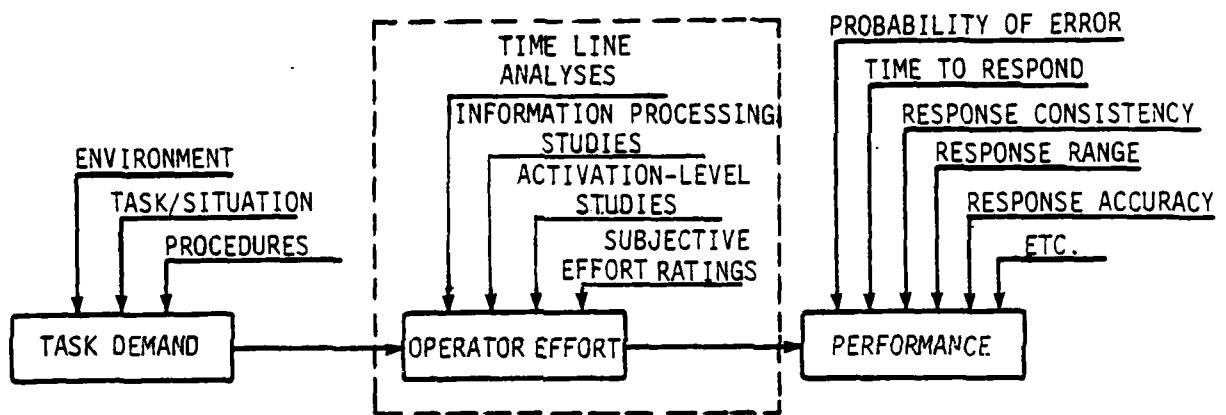
FIGURE 3-6.
ATTRIBUTES OF OPERATOR WORKLOAD

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It would be of great practical interest to be able to provide even a rough estimate of the immediate load placed on the operator, especially in computer-aided man-machine system evaluation. Two related issues are of concern. First, the mapping of task demands to operator capability (and effort) is a dynamic process depending on the operator's strategies and multi-processing structure. Second, the need for immediate (or on-line) measures presents considerable constraints on the methods that may be used.

Considering the first issue, the operator's strategies may be categorically identified through observing a controlled experiment using, for example, the MAU/queueing framework or other methods such as the combined behavioral and discriminant analysis proposed by Rouse (1979). The multiple processor, suggested by variou evidence of multi-channel processors (Sander, 1979), is difficult to determine and is currently under study (e.g., Wickens, 1980). Related to the second issue, the two unique constraints are that the measure should be (1) relatively non-obtrusiveness and (2) easily extractable from short-time estimates (Wickens, 1979). The first constraint requires the method not to absorb the extra reserve capacity of the operator. The second constraint requires the method to provide response and reliable estimates within a limited time window. From the perspective of these requirements, Wickens (1979) has evaluated a number of potential measures, including the following:

(1) Secondary task measures: (a) obtrusiveness, (b) primary sensitivity to response loading.
(2) Time-estimation: (a) uncertain validity, (b) not truly an on-line measure, (c) only one data point per estimated time interval.
(3) Probe reaction time: potential obtrusiveness with increasing probe frequency.
(4) EKG, Sinus Arythmia: (a) influenced by non-workload variables, questionable reliability, (b) not structure specific.

(5)	Pupil diameter: (a) difficult measurement problem for operator in mobile environment, (b) also sensitive to other sources, (c) not structure specific.

(6)	Evoked potentials: (a) requires fairly extensive filtering and application of discriminant analysis, (b) may be contaminated by motor artifacts, (c) slightly obtrusive.

It appears from the above review that the most viable approach for real-time information load assessment is a synthesis of a possible composite approach. It may be a selected mixture of behavioral, subjective, and physiological measures, adapted to the structure and range limits of the task demand. It may be based on a simple, hypothetical formulation that could provide a sensitive indicator for high-load situations (e.g., Rouse, 1979). Or, it may be based on the aggregation of a micro-structure model (Section 2.4.3) or delineation of capacity-structured dimensions. Due to the simplicity and ease of implementation, examples of last two approaches are given in the following paragraphs.

Rouse (1979) has proposed an instaneous workload measure as a product of fraction of attention and the intensity of effort within a given time interval of interest. The fraction of attention might be predicted using a queueing model, while intensity of effort might be measured physiologically or perhaps assessed via subjective measures. If one is willing to assume that hummans always operate to capacity, then the intensity factor can be eliminated. Though, the idea has not been directly evaluated, indirect support of this approach has been given by the following study.

A set of experimental studies based on a flight management task scenario has been performed by Walden and Rouse (1978). The studies demonstrate that the queueing models have the ability to predict the average fraction of attention the pilot is busy (Server occupancy measure) if given a good

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description of event arrival times, task completion times, and the priority of tasks. It appears that the queueing models also enable the model prediction of momentary peak load as a function of input demands. In the most complicated situations, queueing theory only provides bounds for predicted performance measures. However, since the problems that develop in the supervisory control situation deal primarily with top level, discrete events, rather than molecular items, queueing models are well suited to provide gross estimates of the momentary peak load.

Following these findings and observations, Chu and Rouse (1979) then proposed in another set of studies, that the operator load be regulated through a set of thresholds on input demand. When demand exceeded the upper threshold, the upcoming task was routed to the automated function; when demand fell below the lower threshold, the upcoming task was routed to the operator. A look-up table or a fast model had to be maintained to relate the operator effort and performance to the input demand (see Figure 3-7). An experimental study based on a computer-aided flight management scenario demonstrated that the queueing model was capable of representing the multi-task decision making situation, and accurate at predicting such system performance measures as delay time and server occupancy. The simple measure of server occupancy was found to correlate highly with the subjective effort rating in a combined monitoring and control multi-task situation. An adaptive threshold policy for routing input demand, which employed a fast-time model based on a queueing simulation, was shown to significantly improve performance time and was better accepted by the participating subjects compared with a fixed threshold policy.

In summary, a combination of the MAU and queueing model formulations appear to have the most promise in assessing the advanced aircraft operations. The hybrid approach would compensate for operator loading through the following three modes:
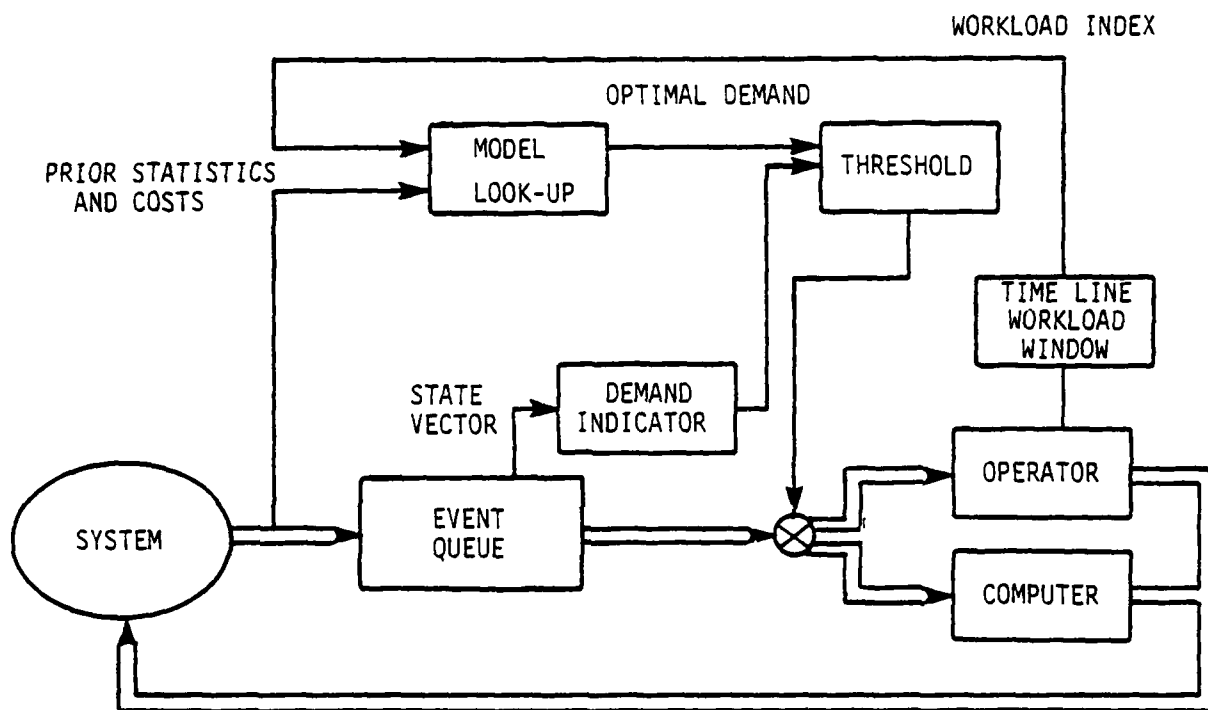
FIGURE 3-7.
ALLOCATION OF DECISION MAKING RESPONSIBILITY BETWEEN
OPERATOR AND COMPUTER IN MULTI-TASK SITUATION

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(1) Adjusting additive factors for evaluating the information (e.g., time-accuracy trade-offs).

(2) Adjusting a threshold of information presentation (e.g., information routed to automated operator).

(3) Adjusting the allocation of responsibility between pilot and computer (e.g., based on utility dimensions or capacity dimensions).

The criteria for adjustment would take the form of:

(1) The measured task performance.

(2) The predicted task load, from indicators of complexity, speed, and task interference.

(3) The subjective operator input.

(4) A synthesis of the above.

3.4.4 <u>Human-Computer Interface</u>. The variety of forms of interaction between the aiding system and the human operator necessitates the development of a complex interface. The operator must be able to input various problem parameters, override machine choices, observe aiding system recommendations, and be appraised of fully automated functions. In certain instances, the operator (or expert) must even be able to enter new functions to the system and be given explanations for machine choices.

An input panel to the system should perform the following specific functions:

(1) Probability Entry - The operator may provide subjective estimates of the likelihood of key events. The estimates should be made either in likelihood ratio form or as direct probability estimates. These estimates would override the stored event probabilities.

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(2) Attribute Importance Ratings - The operator may change the system's decision policy by altering or zeroing out certain of the attribute weights. This can be done by assigning dedicated keys to each attribute or to pre-established policies--offensive, defensive, fuel conserve, etc.

(3) Situation Classification - The specific situation may be recognized and input by the operator. Some exemplary situations are fuel criticality, excess time stress, and tactical advantage. The input then changes the system stage.

(4) Own Confidence - The operator may input an estimate of confidence in manual control of a given function. This is similar to the probability input function.

(5) Overrides - The operator may override any of a number of machine functions--sensor recommendations, display formating, information content, action choice, or level of aiding. Again, dedicated keys appear necessary for this function.

The display requirements are similarly extensive:

(1) System Status - The status of the aiding system in terms of the current processing function and control allocation state should be displayed using indicator lights or illuminated keys.

(2) Recommendation - Display of the favored information acquisition or action choice may have to be shown graphically if trajectory information, fault location data or other complex information is involved. Otherwise, an alphanumeric CRT display is indicated.

(3) System Confidence - An indication of the aiding system confidence in the recommended choice should be shown using a multi-point scale.

(4) Explanation of Choice - An optional capability is the system explanation of its recommendations. This is a common feature of the production rule format, and requires both keyboard query and CRT display.

In sum, the man-computer interface can probably be supported with a multi-purpose CRT screen and a keyboard entry device. The keyboard should include certain dedicated, back-lit keys and the CRT would be required to provide both graphic and alphanumeric displays.

3.5   Transition Rule Formulation

The previous sections have indicated the need for varying the decision model form and aiding level according to the situational conditions. In situations of low model confidence and low operator load, for example, a passive mode may be best. Under conditions of time stress, dominance by one decision alternative, and non-criticality of outcomes, an autonomous model-based execution of the decision would be warranted. Some type of situation-based control of the model form and aiding level appear necessary for effective system operation.

The forms of model-based aiding include:

(1) Passive training.
(2) Presentation of aggregated data (probabilities, likely outcomes, etc.).
(3) Model-based information recommendation.

(4) Model-based action recommendation.

(5) Automated information selection.

(6) Automated information system management (sensor adjustment, information selection, display formating, action recommendations).

The model-based recommendation and automation functions may involve use of a full MAU/queueing model or a truncated portion of it. In certain circumstances, some dimensions of the model will be irrelevant or misleading. For example, in a final target approach phase, the fuel or enemy detection attributes may need to be zeroed out. In situations where no previous model training has occurred, the model should be shifted to a unity-weight formulation.

The majority of the knowledge regarding the relationship between the above situation conditions and aiding forms appears to be heuristic in nature. For example, there is normally no closed-form, consistent functional model of the relationship of aiding system confidence to performance with each level of aiding. Instead, there are the situational criteria for transitioning between the various model forms and aiding levels include the following sets of ad hoc and sometimes inconsistent situation patterns to aiding forms:

(1) System confidence. The system experience or expected performance with the type of decision being made (see Section 3.4.2).

(2) Operator load. The available capcity of the human operator (see Section 3.4.3).

(3) Decision time stress. The number of decisions per unit time (weighted by decision complexity).

(4) Operator capability. Previous performance in the particular phase of the task.

(5) Task component. The type of behavior being performed--moni-
toring, information acquisition, targeting, etc.

The production system appears to be the simplest and most effective means
of keying the aiding form to the task situation and to the operator needs.
Production systems are a form of knowledge-based systems well suited for
pattern-directed process control, and contain among others components the
basic unit of the production rule, which consists of (1) an antecedent or
condition, and (2) an action or consequence. For example, "If you are
flying a surveillance mission and radar indicates a threat, you should
perform an avoidance maneuver." The conditions are (1) flying a surveil-
lance mission, and (2) radar indicates a threat. The action is to make an
avoidance maneuver. The advantage of the production rule format is that
highly specific knowledge can be accessed quickly. The rules are compact,
transparent to the user, and easily modifiable. Finally, the knowledge
chunk represented is compatible with the types of relations present in
information management--discrete mappings between patterns of situational
conditions, model forms, and aiding levels.

Production rules have two additional features which enhance their useful-
ness. Each rule has associated with it (1) a confidence in its truthful-
ness or a probability of its success, and (2) an estimate of the cost or
difficulty of the action. To select a rule to activate, the difficulty
information may be combined with the confidence information. This results
in the choice of the most cost-effective action. The use of confidence
ratings also allows partially inconsistent rules to be used.

A production system is a combination of three components: (1) a collection
of production rules (already discussed), (2) a workspace, and (3) a control
mechanism. The workspace contains the complete description of the system's
current state or situation. This description consists of the current aiding

mode, model training level, model confidence, decision criticality, operator load, and response time demands, among other factors. The antecedent of a rule describes, or is matched against, the contents of the workspace. If a production is applied, the consequence or action modifies the workspace. The third component, the control mechanism, provides conflict resolution procedures if several antecedent matches are present. This may be accomplished using such criteria as rule orderings, precedence networks, or measures of recency of firing of each rule. Detailed descriptions of these functions of production systems are given in Barnett and Bernstein (1977), Davis (1977), and Newell (1976).

The implemented form of the production system is shown in Figure 3-8 (adapted from Hayes-Roth, Waterman and Lenat, 1978). The system consists of four modules, the knowledge base, control mechanism, workspace, and interface. The knowledge base contains both problem knowledge, in the form of production rules and fact files, and meta-knowledge, strategies for using the system's capabilities. The control mechanism drives the system. It coordinates the firing of the productions and supervises search procedures involved in such functions as trajectory optimization and sensor direction. The control mechanism also possesses the potential for explaining its actions and reasoning processes. The workspace carries the current task situation and the agenda of applicable results under consideration. The last module, the interface, provides interactive communication between the user and the system. The interface allows for directed acquisition of data (outcome frequencies, load levels, new production rules, etc.) and for the addition or modification of data in the knowledge base. Normally, expert input is the source of the production rule data, while onboard sensing should provide the system data. An example of a rule generated in this fashion is as follows:
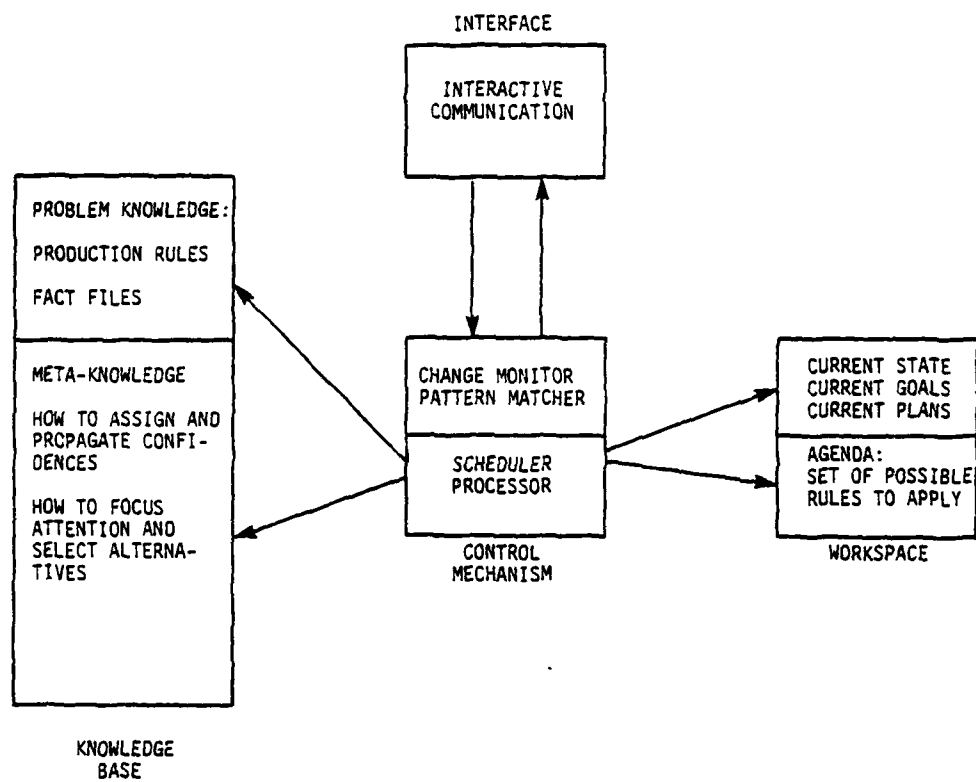
INTERFACE

```
┌─────────────────┐
│   INTERACTIVE   │
│  COMMUNICATION  │
└─────────────────┘
```

```
┌──────────────────────┐          ┌──────────────────┐          ┌──────────────────────┐
│ PROBLEM KNOWLEDGE:   │          │  CHANGE MONITOR  │          │   CURRENT STATE      │
│                      │          │  PATTERN MATCHER │   ───►   │   CURRENT GOALS      │
│ PRODUCTION RULES     │          ├──────────────────┤          │   CURRENT PLANS      │
│                      │          │    SCHEDULER     │          ├──────────────────────┤
│ FACT FILES           │          │    PROCESSOR     │   ───►   │   AGENDA:            │
├──────────────────────┤          └──────────────────┘          │   SET OF POSSIBLE    │
│ META-KNOWLEDGE       │             CONTROL                    │   RULES TO APPLY     │
│                      │             MECHANISM                  └──────────────────────┘
│ HOW TO ASSIGN AND    │                                           WORKSPACE
│ PROPAGATE CONFI-     │
│ DENCES               │
│                      │
│ HOW TO FOCUS         │
│ ATTENTION AND        │
│ SELECT ALTERNA-      │
│ TIVES                │
└──────────────────────┘
     KNOWLEDGE
       BASE
```

FIGURE 3-8.
PROCUDTION SYSTEM STRUCTURE

<u>If</u>: the operator load is above .7 <u>and</u> the system confidence is
above .9 <u>and</u> the task is subsystem monitoring, <u>then</u> set the aiding
level of the system to automated information management.

Additional rules would then be invoked depending on the current aiding
level. These rules specify the ordered sequence of actions to take in the
transition--coordination of sensors, tranmission of data, alerting of
operator to new function, etc.

Other elements of the information management system may also be facilitated
using production systems. Information may be pre-filtered according to
such constraints as age, content, and length, before processing by the
MAU/queueing model begins. Certain action options may be similarly pruned
from consideration by the mode through a few "threshold" rules.

4. A SIMULATION EXPERIMENT

4.1 Overview

Two types of simulation and testing have been planned for the combined MAU/queueing model. The first simulation is a purely computational Monte-Carlo simulation, embedded with statistical representation of hypothetical operator activities. This allows rapid testing of the behavior and performance of the model prior to the second simulation, the human subject experimentation. A discrete-event digital simulation program was developed for the combined multiple-threat and flight management situation. The simulation used an activities scanning approach (Fishman, 1973) to represent a $(M/E_k/1):(NPRP/N/M)^*$ queueing system.

A simple case including three independent classes of events described in Section 3.3.5 is considered. Task score and performance time measures were compared among MAU-based policies and other priority policies typically used in multi-task operating systems. Initial results suggest that the value-based model is suitable for concurrent evaluation of information source and event sequence. The management concept based on the MAU model seems to be superior to those based on traditional priority management. The implications of this study and the plan for experimental validations are also discussed.

4.2 Task Simulation

The major perspectives that are included in the hypotheses tested in this study are:

(1) The management concept in supervisory control of advanced aircraft provided by the information value model is superior

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*The symbols represent a Poisson arrival/Erlang service time distributions with single server and non-preemptive priority discipline among N processes with M waiting spaces.

to those provided by the priority management of traditional
operating systems. The judgment will be based on user
acceptance and performance measures tested over a range
of supervisory control tasks.

(2) Implicitly implied by the above hypothesis is the assumption
that the information value model can be effectively used
in a continuous monitoring and control situation, i.e., the
MAU model is suitable for concurrent evaluation of infor-
mation source and event sequence.

(3) A proper index of information load can be constructed and
will be useful as an indicator of the level of loading
resulting from model-based information handling requirements.

With these perspectives in mind, a task simulation was configured to
resemble information handling tasks in multiple intercept operations.
It will be used in the second program year to evaluate the MAU/queueing
model for continuous monitoring and control functions and to investigate
the behavioral issues of aiding. This evaluation process will be dis-
cussed in Section 4.2.4. One potential difficulty has to be resolved
before the evaluation process can be successfully carried out.

As there are numerous task and decision variables affecting overall
system performance, it would be very difficult to illustrate these
effects using a human subject experiment. Therefore, computer simulation
experiments are performed first, which can provide information about
numerous variables over thousands of decisions. For this purpose, the
success of the computer simulation depends very much on its ability
to accurately represent the task situation. In the following sections,
a hypothetical task situation is described and then a set of variables
is defined to represent the important dimensions of the task situation.

4.2.1 <u>Experimental Situation of Advanced Aircraft</u>. In the earlier
study, a task simulation orginally had been configured to resemble multiple
intercept operations (Steeb et al. 1979). The operator selected infor-
mation regarding threats of uncertain capability and location. The
information options available to the operator differed in threat discri-
mination capabilities, costs, time delays, and potential of detection.
The information selected was subsequently used to take aggressive or
avoidance actions.

The simulation can be extended to include additional supervisory tasks.
It is planned to provide a continuous time version of the multiple threat
task plus sub-system monitoring/checklist verification and aerodynamic
status tasks. The operator would have uncertainties regarding each un-
monitored process. The build-up in uncertainty can be represented using
stochastic functions, as described in Section 3-3. The forms of display
in the task represent the display and communication console of the
advanced aircraft. For example, the environmental situation may be
represented by sets of threats that appear at random time and positions
at the upper edge of the display and move downward at a constant velocity.
A threat event will require the operator to move the vehicle symbol
horizontally to avoid the threats, or the operator can remain on course
and take an aggressive action against one of the threats. The subsystem
event will require the operator to perform a hypothetical checklist
procedure. The maneuver/navigation event will require a series of inter-
mittent control actions.

This multi-function task, with its use of multiple supervised processes,
each with several information options, also lends itself to studies of
behavioral issues. Aiding can involve probability aggregation, process
recommendation, information recommendation, and automation. The behavior-
al responses can be observed regarding model confidence, aiding level,
operator load, and perceived control.

Within this experimental situation, important situation variables in-
clude the complexity of the maneuver, the level of threats, the number
of subsystems, and the depth of the checklist procedure. Equally impor-
tant are the availability of the autopilot, the level of detail or target
information, the subsystem checklist (branching) complexity, the distri-
bution of event arrivals among tasks, and many other environmental, air-
craft, and subsystem parameters.

4.2.2 Simulation Program Flow. In order to allow rapid checkout of
system operation and model function within the above test scenario, a
discrete-event digital simulation program was developed. A computational
Monte-Carlo simulation of stochastic processes in the system and an auto-
mated operator model for information evaluation was used, allowing the
testing without the necessity of deriving a closed form solution of in-
formation system dynamics, an intractable problem at this level of
complexity. A FORTRAN simulation program similar to the one demonstrated
in Chu and Rouse (1979) was developed for the combined multiple-threat
and flight management situation. The simulation used an activity scanning
approach (Fishman, 1973) to simulate an ($M/E_k/1$: (NPRP/N/M) queueing
system. The fundamental logic flow of this approach is described in
Figure 4-1, to be explained in the following paragraph.

The approach considers the operator's information handling task as a
single server queueing problem, in which the status of the task situation
needs to be updated either when a new arrival occurs, or else at the
completion of a service. After one of the above two activities is identi-
fied, simulated time is advanced to the time of the expected event or to
the time of service completion. If an arrival has occurred, the time for
the next arrival is scheduled, using the given arrival distribution. If
a service is completed, the actual system changes need to be recorded, and
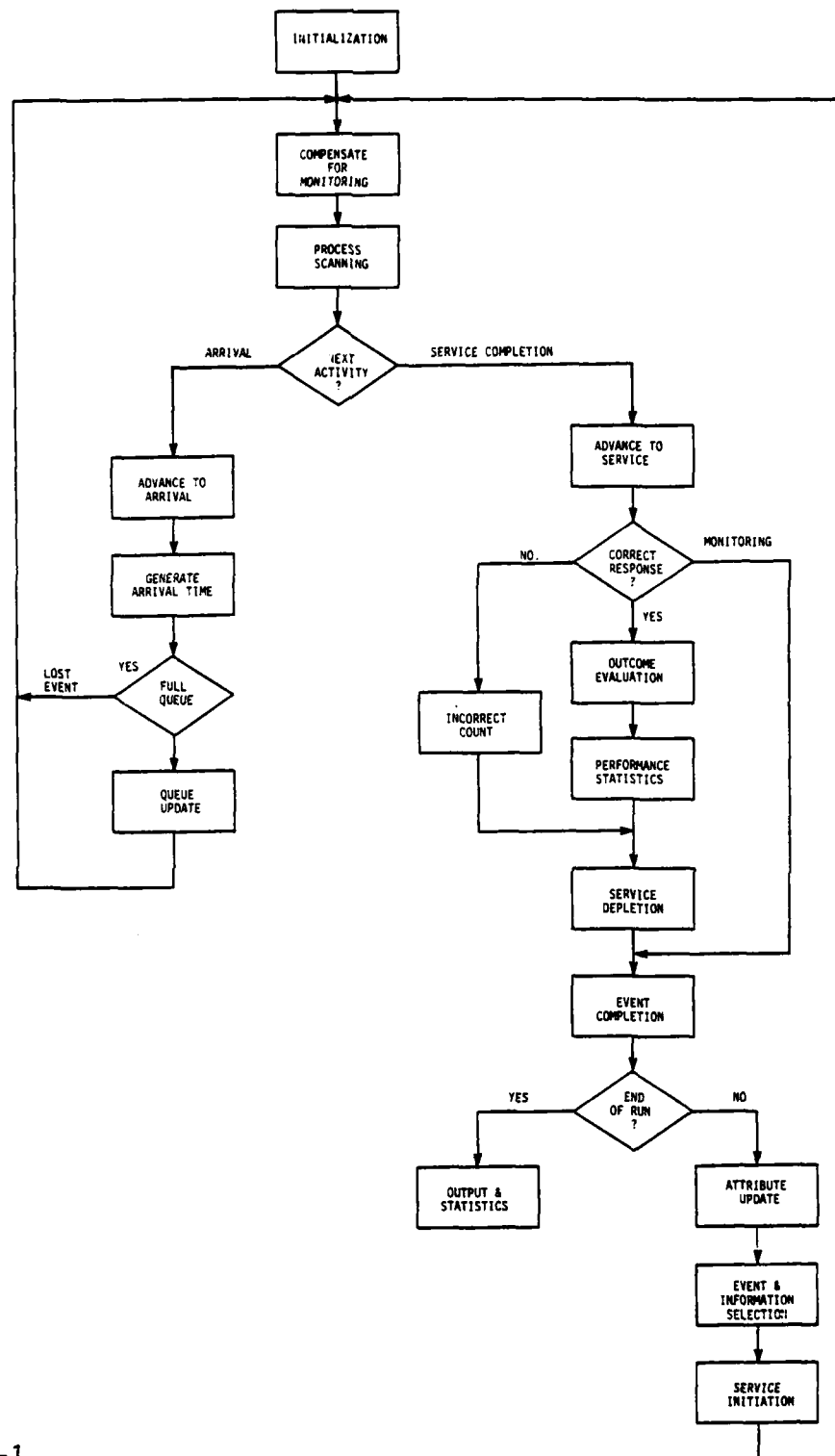then an event and the suitable information source need to be selected for

FIGURE 4-1.
COMPUTER SIMULATION FLOW DIAGRAM

a follow-on service. By checking these conditions and timing, the program logic used in the activity scanning approach determines when the next event occurs, advances time accordingly, and recycles through the service activity. As the program diagram shows, the process starts at time 0, moves from one event to the next, one decision epoch to another, generates the probability and utility updates using the MAU model, rank-orders the information sources, and records actual system changes. The process continues until the time limit is exceeded or when the next event represents the end of the simulation, at which time the performance measures and statistics of interest are calculated.

For the task flow represented at this level of abstraction, the situation variables described in the last section are further analyzed, and a set of quantifiable, independent parameters are identified that can sufficiently represent the situational variation. These parameters are discussed in the next section.

4.2.3 <u>Simulation Parameters</u>. Two classes of parameters are used to quantify the multi-task information handling situation. The first class relates to the queueing process and the second class relates to the information value model. The queueing process parameters include the following:

(1) Perceived arrival rates, for the three types of events: threat, maneuver and subsystem (λ_i, i = 1, 2, 3).

(2) Average service rates, for each type of event and selected information source (μ_{ij}, i = 1, 2, 3, j = 1, 2, 3).

(3) Erlang service parameters, k_{ij}, used to match the service time distributions obtained from the experiment.

(4) Scanning time and detection time, obtained from the experiment or estimated from previous findings.

(5) Probabilities of false alarm, missed event, and incorrect service, estimated from the experiment.

The information value model parameters include the following:

(1) Payoffs for completing the service of events.
(2) Risk accrued per unit time delay of service.
(3) Loss for incorrect actions.
(4) Initial cost of communication.
(5) Initial attribute weight.
(6) Probabilities of outcome state for a given information source and for a given event.

In the experiments, the process and model parameters were determined for the following simple case. (1) Event arrival rates and service rates were all uniform among classes of events and corresponding information sources. (2) Three levels of arrival rate (i.e., 0.005, 0.010, and 0.015 events per second per class) and one level of service rate (0.05 events per second) were used. (3) Information attribute levels were determined utilizing a set of relationships derived in Section 3.3.5. (4) The *outcome-related parameters, such as payoffs for event service,* losses for incorrect actions, initial cost of communication, probabilities of outcome states with given information choice, and the loss accrued due to service delay, were determined in a manner to provide a suitable level of decision complexity. (5) The attribute weights were all set to be equal to one.

4.2.4 Performance Measures. The close coupling of operator and aiding system requires evaluations of (1) the overall system performance, (2) the performance of the queueing model, and (3) the performance of the value model. The overall system performance may be described by the following measures:

(1) Number of hits, avoidences, clearance, and incorrect actions.

(2) Total cost of communication.

(3) Average task completion times based on either individual or all classes of events.

(4) Fraction of attention required of the operator.

(5) Fraction of time when system is in proper operation (i.e., subsystem functional, threat cleared, and vehicle on-course).

The first two measures can be combined into a single index, the score. The score is derived from the following relationship:

$$SCORE = (PAYOFF) - (PENALTIES + COMMUNICATION COSTS)$$

In this initial year study, the task score and completion time measures were found more responsive that the rest of the measures. However, all of the measures will have to be considered in the next year's study, when the scope of study will be expanded.

The performance of the value and queueing submodels may be evaluated in terms of behavioral prediction, operator acceptance, and information management performance. Prediction refers to the study of the model to predict operator behavior in terms of actual information selection and task completion time. Outputs of the value submodel may be compared to actual operator choices during the unaided sessions. Output of the queueing submodel may be compared to actual subtask completion time and fraction of attention given to a particular task. The validation of the overall MAU/queueing is shown in Figure 4-2. A man-machine simulation experiment will be performed to provide quantitative data of both operator activities (for model input) and operator performance (for model comparison). For simplicity, the performance comparison will be performed off-line. After the model is validated, on-line aiding schemes employing the MAU/
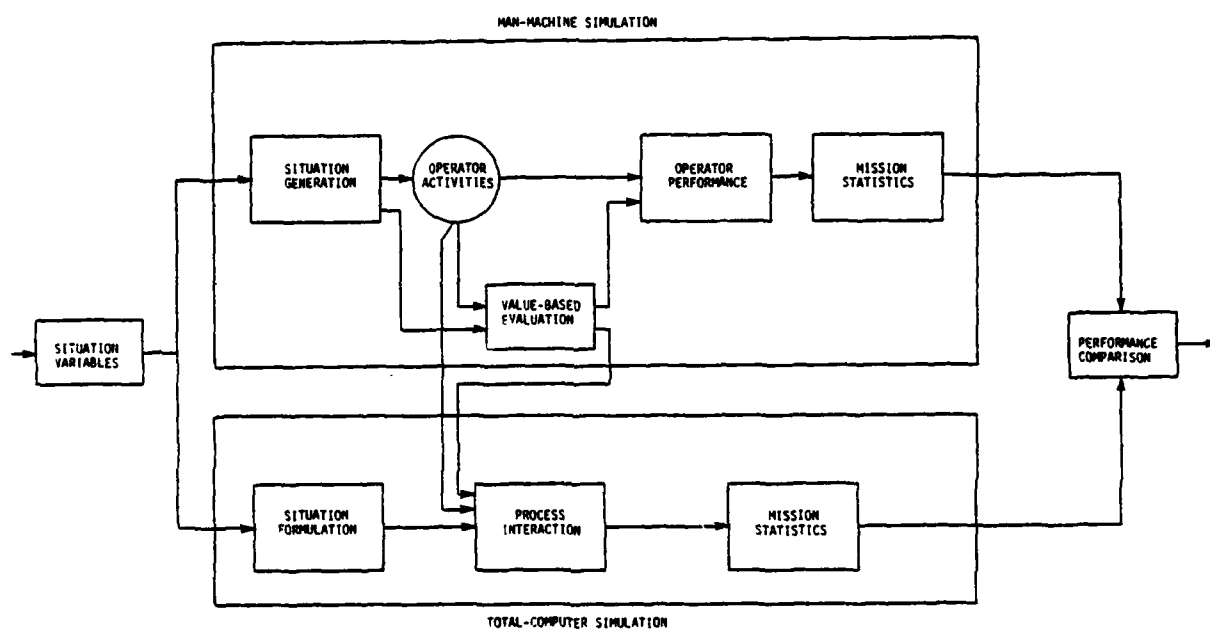
MAN-MACHINE SIMULATION

SITUATION GENERATION → OPERATOR ACTIVITIES → OPERATOR PERFORMANCE → MISSION STATISTICS

VALUE-BASED EVALUATION

SITUATION VARIABLES

PERFORMANCE COMPARISON

SITUATION FORMULATION → PROCESS INTERACTION → MISSION STATISTICS

TOTAL-COMPUTER SIMULATION

FIGURE 4-2.
EXPERIMENTAL VALIDATION OF MAU/QUEUEING MODEL

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Queueing model discussed in previous chapters will *then be implemented.*
For the current year, the MAU/Queueing model in total computer simulation
has been developed. Only a limited set of situation and performance
variables was considered. The results are presented in the next section.

4.3   Results of Simulation Experiments

The results that follow were obtained using the Fortran simulation
program described in earlier sections. The first simulation experiment
considered the effects of different event selection policies -- fixed-weight
MAU, First-come-first-served (FCFS), and Head-of-the-line (HOL) policies.
The FCFS policy is the one that schedules the service according to the
time of arrival. The HOL policy is the one that schedules the service
according to the lines of priority and then the time of arrival within
the priority line. All three policies use the MAU model for information
source selection. The results of the first experiment are presented in
Section 4.3.1.

The second simulation experiment considered the effects of different
disciplines for the selection of information sources -- MAU, Time-sensitive,
and Accuracy-sensitive disciplines. All three disciplines used the MAU
model for event selection. The results of the second experiment are
presented in Section 4.3.2. All the results are based on the computer
simulation of 360,000 seconds (with a corresponding number of events
ranging from 54,000 to 162,000 approximately, depending on event arrival
rate).

4.3.1 Evaluation of Event Selection Policies. A comparison of average
event completion times under three event selection policies is given in
Figure 4-3. As expected, the FCFS policy produced essentially the same
average completion time for all three classes of events, while the HOL
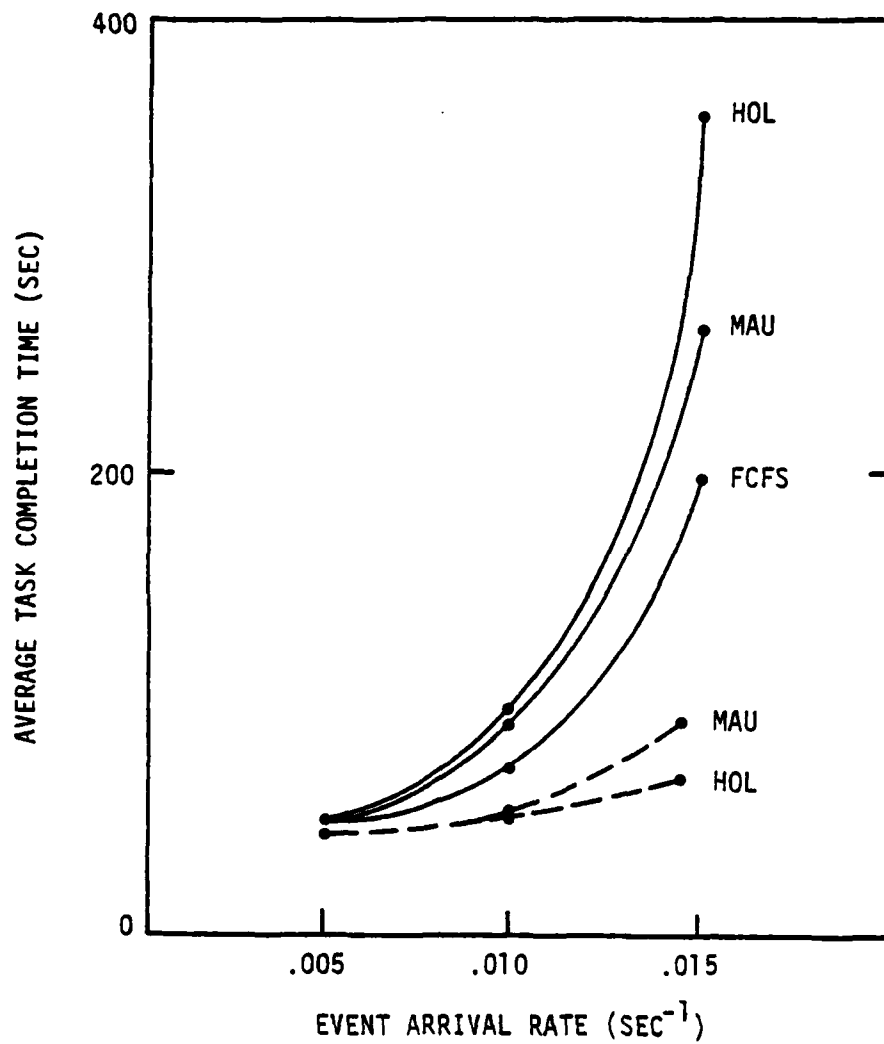policies produced both the highest and the lowest event completion time.

FIGURE 4-3.
AVERAGE TASK COMPLETION TIMES AS FUNCTIONS
OF ARRIVAL RATE AND SELECTION POLICIES

The MAU model produced a modest variation of performance among classes of events. If the extremely long completion time is the only concern, then the FCFS policies are favorable to the other policies, where event arrivals are discriminated and served according to their priorities. On the other hand, if event urgency is of primary concern, it appears that HOL would be appropriate when there is a clear order of priority among classes of events. Overall, the performance of MAU policies appear to vary between these two extremes, and if the weighted completion time is used for comparison, the MAU policies are most likely to be favorable to those other two policies.

Instead of using weighted completion time, the total task scores for the three policies were compared and are shown in Figure 4-4. It appears that the MAU policies would always generate the highest score among the three, especially when task demand was high. This was due to the fact that the FCFS and the HOL policies were lop-sided in weight distribution, either insensitive to event urgency or event time expenditure. The estimate of operator time occupancy, i.e., the fraction of time the operator was busy in performing the task, was essentially the same for all three policies and proportional to the level of input demand. This result reflects that the situation represented is a highly simplified one.

4.3.2   Evaluation of Information Source Selection. In order to evaluate the effects of various disciplines on information source selection, some of the values of situation parameters in the previous experiment have been modified. The previous experiment assumed a zero probability of the operator's incorrect service (PI), the probability that a service is not completed and has to be repeated. This may be unrealistic. Further, the most common trade-off among information sources is one between incorrect service and time expenditure, the typical time-accuracy trade-off. It was assumed in this second experiment that this trade-off between
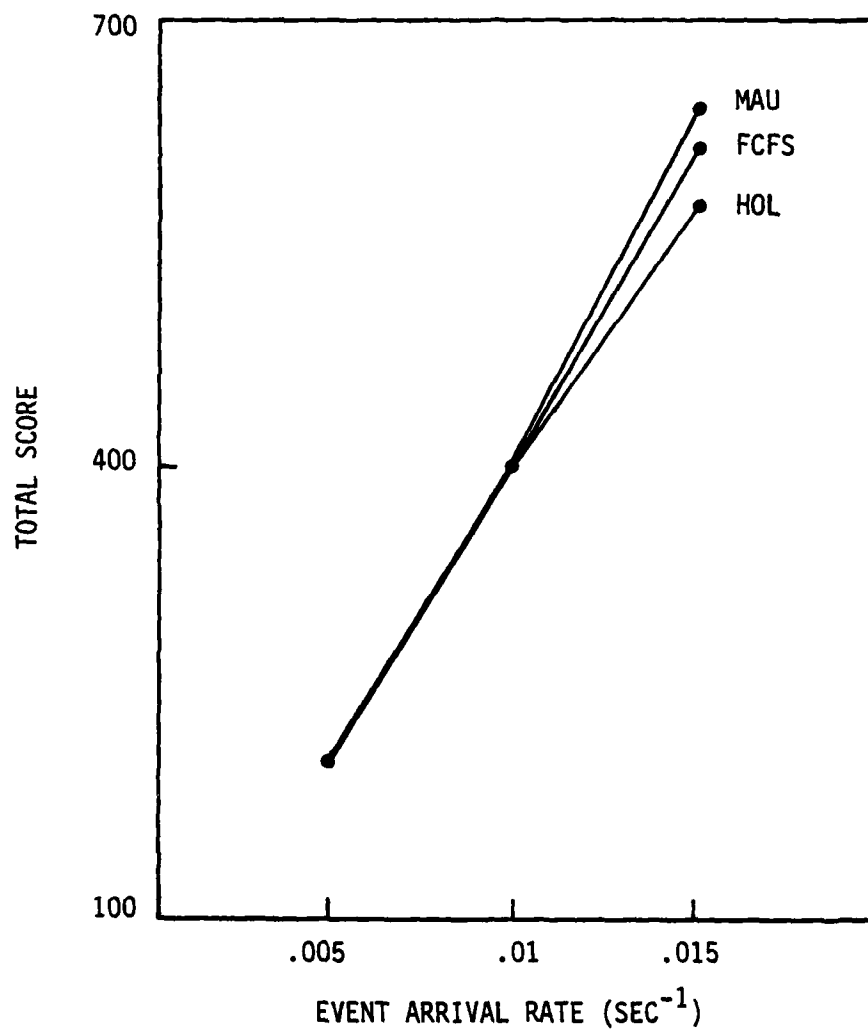
FIGURE 4-4.
TOTAL SCORES AS FUNCTIONS OF ARRIVAL
RATE AND SELECTION POLICIES

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information source might be represented in an inverse linear or exponential relationship. An example is given by $PI = a \cdot e^{-bk}$, where a and b are non-negative constants and the interger k is the Erlang service distribution parameter representing the equivalent number of service stages for a particular information source.

With the above relation embedded in the program, experiment runs were conducted to test the responsiveness of various disciplines to the operator's trade-off strategy represented by a range of a and b values. The results are shown in Figures 4-5 and 4-6. As expected, the accuracy-sensitive policy (with consistent selection of high accuracy information) has produced the highest waiting time and lowest number of incorrect services, while the MAU and time-sensitive policies produce a low average waiting time and a higher number of incorrect services. Overall, the MAU-directed policies produced the highest scores. This is due to linear trade-off functions already incorporated in the MAU model which has weighed speed and accuracy factors.

The two experiments described above have provided preliminary results of the use of information value models in continuous, multiple-source information handling situations. The experiment, assuming an automatic operator with simplified activities, did not consider various behavioral issues discussed in Section 3.4. Besides, various parameters used were arbitrarily selected. Therefore, the data obtained can only be used as an initial, functional evaluation of the combined MAU/Queueing model, and cannot be generalized to other task situations. Nevertheless, the results suggest that the information management concept based on a prescriptive MAU and descriptive Queueing model seems to be superior to and more flexible than those based on traditional priority policies or selection disciplines.
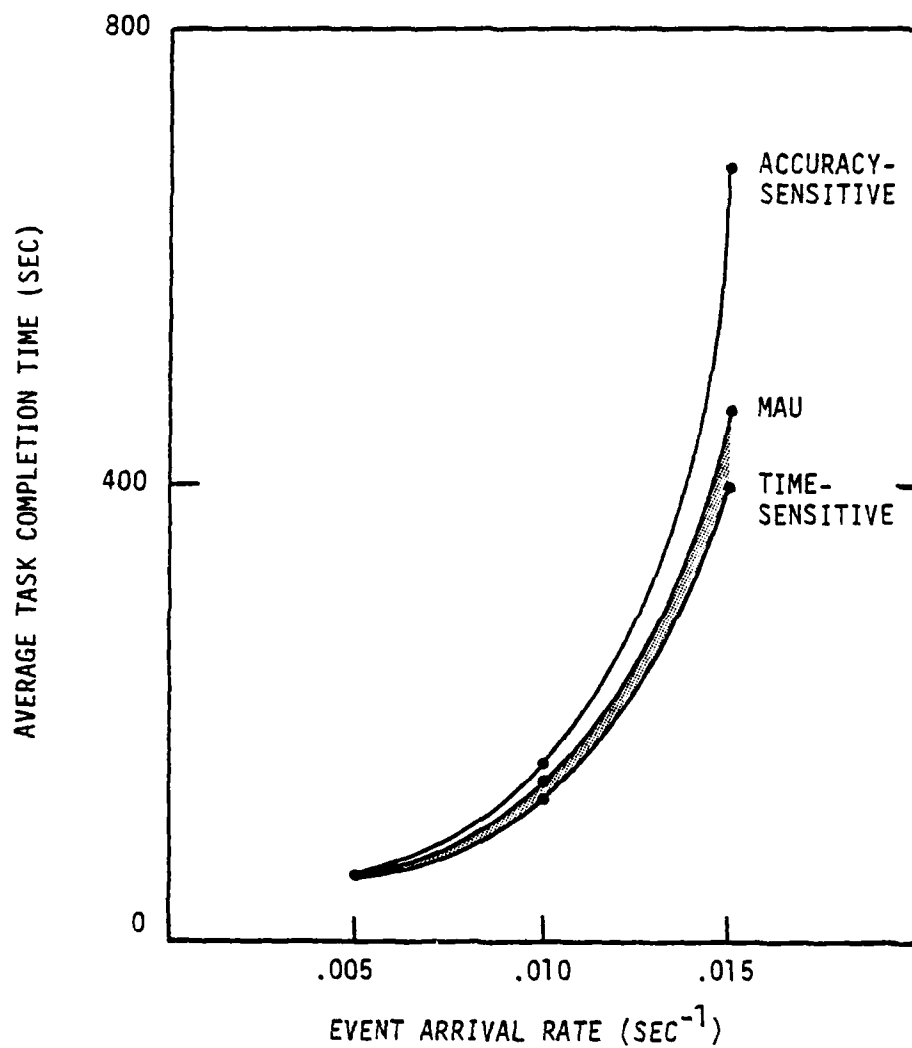
FIGURE 4-5.
AVERAGE TASK COMPLETION TIMES AS FUNCTIONS OF
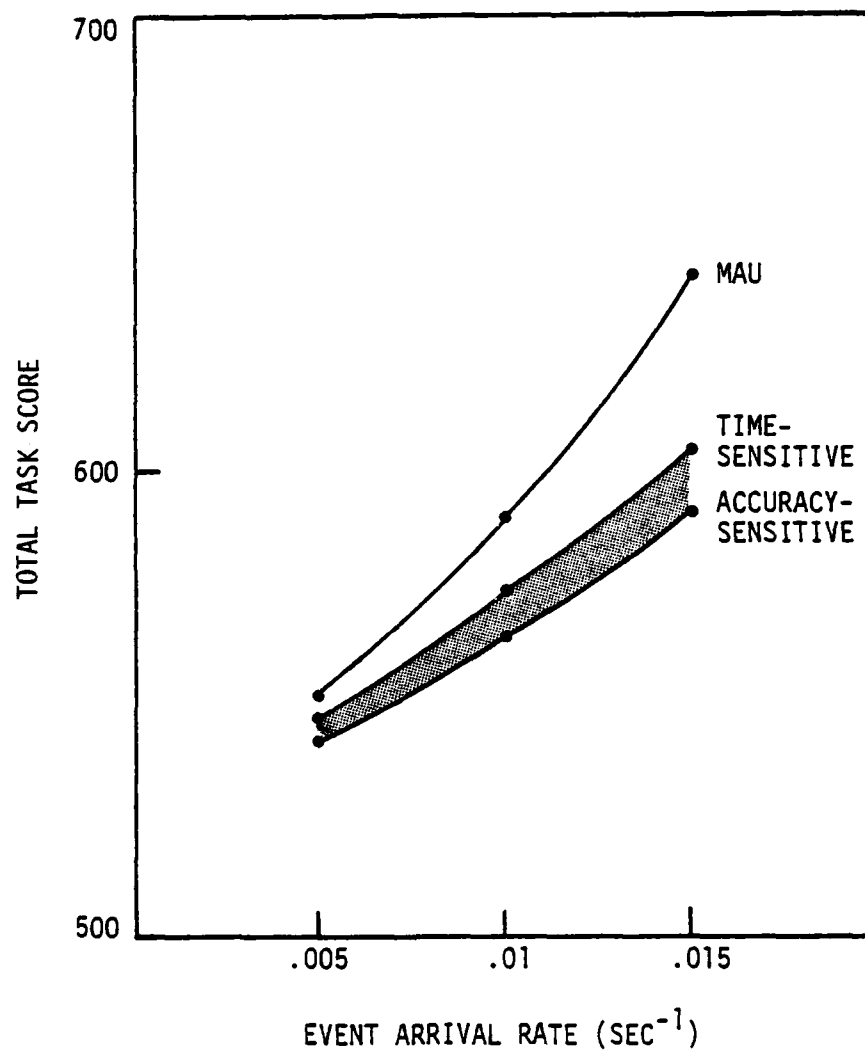ARRIVAL RATE AND SELECTION DISCIPLINES

FIGURE 4-6.
TOTAL TASK SCORES AS FUNCTIONS OF ARRIVAL
RATE AND SELECTION DISCIPLINES

5. CONCLUSIONS AND FUTURE DIRECTIONS

5.1   Overview

The computer simulation study demonstrates the potential of a value-based model for (1) information source selection, and (2) event sequence selection in multi-task, continuous information handling in advanced aircraft. The combined MAU/queueing model is a new prescriptive behavior model of the operator's activities in information selection, acquisition, and processing for decision. The model, as a system model, will be able to account for both subjective factors (information load and confidence) and objective, intrinsic task conditions (environment, communication, procedure execution and intermittent control, etc.). Information flow is modeled as a queueing process that possibly can be regulated by the value-based model. The result is a set of interacted stochastic subprocesses that form a model for predicting impact of information flow and display over crew performance.

Although the MAU/queueing model has not been experimentally evaluated, each model separately had been tested for multiple-intercept tasks (Steeb, et al, 1979) and flight management tasks (Chu and Rouse, 1979). In addition, for this initial implementation of the MAU/queueing model, many important behavioral aspects have been simplified. Nonetheless, even with its current state of development, with minor modification in value structure and queue control discipline, the MAU/queueing model could be used to simulate the experimental situation of interest and to identify variables of importance related to advanced aircraft operations.

5.2   Automated Information Handling

Aiding in information handling provided by the combined information value and flow concept may take the form of (1) event sensing, (2) data fusion,

(3) problem recognition, (4) source selection, (5) event sequencing, (6) consequence evaluation, and (7) event (procedure) selection.

(1) Event Sensing. This aspect of the information handling process involves the sensing and communication of environmental conditions, threat type and location, own force status and other relevant information. The sensors may include video, infra-red, radar and on board detection systems. The information may need to be routed adaptively from the point of acquisition to the appropriate processing and display unit.

(2) Data Fusion. Data fusion is the aggregation of the information obtained from the various sensors and the generation and testing of situational hypotheses. In this way, the local or global situation estimate is updated using production rules or Bayesian methods. Queueing model of correlated inputs (Gopinath and Morrison, 1977) may be considered.

(3) Problem Recognition. Problem recognition involves the monitoring of tolerance ranges around critical variables (fuel limitation, flight surface constraints, launch acquisition region, etc.) to determine if correct actions need to be initiated. Problem recognition in advanced aircraft supervisory control tasks involves tolerance checks either on the current state or on the predicted future state.

(4) Source Selection. Simultaneous consideration of multiple alternatives protrayed against multiple criteria quickly becomes too complex for the operator to resolve. Computer based aggregation of the various factors is typically faster and more consistent than is possible by the operator. The

multi-attribute utility model represents the policy of the
specific user; it has access to the factors characterizing
each information choice, and it can be linked to the on-
board information control system. The model can be configured
to automatically scan the available information source,
select the immediately most useful source, and display it to
the operator.

(5) <u>Event Sequencing</u>. Once data has been collected from the
sensors, situation estimates updated, and potential problems
recognized, then procedures associated with the event must
be sequenced that will resolve conflicts and achieve goals.
The sequenced actions may be synthesized using one or more
of the following approaches: (a) means-ends analysis, (b)
backtracking, (c) hierarchical planning, and (d) production
system.

(6) <u>Consequence Evaluation</u>. Implicit in the value-based event
sequencing is the concept of an evaluation function--max-
imization of tactical gain, minimization of vehicle loss,
minimization of operation time, optimization of jamming/
communication, etc. Each candidate course of action should
be scaled along the common set of criterion dimensions.
Weighting of the choices in importance then allows systematic
comparison of the possible action choices. If the criterion
dimensions are probabilistic in nature, e.g., detection of
communications, tactical gains, or losses sustained, then
the expectation of the outcome is used in the evaluation.
Additional risk factors can be added if the selection policy
is not risk neutral.

(7) Event Selection. Event (procedure) selection involves the
comparison by the affected subprocesses of all candidate
events, since the affected subprocesses may have different
goal sets, and may compete for resources under different
criterion functions. In this case, it is necessary to
bargain or to select according to aggregated value judgment.

5.3 Future Directions

5.3.1 MAU/Queueing Model Extensions. The domain of adaptive, user-based
decision aids can be extended by elaborating the structure and the function
of the model-controlled information flow system. Experiments are currently
underway to investigate the possibility of expanding the MAU/queueing
model to include continued sampling and preemptive task priority. Our
previous study by Steeb et al (1979) suggested a statistical decision
theoretic approach, employing combined Bayesian and integration theories
(Shanteau, 1970) implemented in appropriate parts of the decision tree.
An alternative approach is a queueing process with selected probability
of event feedback to the input of the information queue. Extensions will
also be made by incorporating various preemptive and non-preemptive control
disciplines, resulting in a detailed subprocess model.

5.3.2 Man-Machine Experimentation and Model Validation. The validation
of the MAU/queueing model for continuous information handling tasks and
the investigation of behavioral issues of automated information management
will both be accomplished using a multiple-intercept operation scenario
in advanced aircraft. It is planned to provide a continuous time version
of the multiple threat task plus system clearance and aero-dynamic status
tasks. The operator would have uncertainties regarding each unmonitored
process. The build-up in uncertainty can be represented by using stochastic
functions. The forms of display in the task represent the display and
communication console of multiple supervised processes, each with several
information options.

Future work will concentrate also on investigating critical behavioral
issues regarding operator acceptance and confidence in the aiding, and
will provide techniques on on-line transitioning between forms of aiding
as the task situations change. The intent will be to determine functional
relationships between the various factors and operator acceptance of aid-
ing. These functional relationships will be used to develop specific
production rules for determining the appropriate form of aiding in super-
visory control of multiple-process systems.

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